The preservation and conservation of ink jet and electrophotographic printed materials

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THE PRESERVATION AND CONSERVATION OF INK JET AND ELECTROPHOTOGRAPHIC PRINTED MATERIALS

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A thesis submitted in partial fulfilment of the requirements of the Open University for the degree of Doctor of Philosophy in Chemistry

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Variable print quality

ABSTRACT

This research project has investigated the light fastness of ink jet and electrophotographic printed materials by the means of an extensive accelerated and natural ageing test programme. The effect of visible radiation of different wavebands on the deterioration of a selection of ink jet printed materials has also been assessed. The findings of the research indicate that all of the ink jet printed materials tested are sensitive to light and should not therefore, be put on permanent display. Most of the ink jet printed samples exhibited greater light sensitivity to the shorter wavelengths of the visible spectrum, than the longer wavelengths, with damage decreasing as wavelength increases. This relationship was not evident with the cyan and blue printed samples, which showed that their light sensitivity was determined by the spectral absorption characteristics of the printed patch. Some of the ink jet printed materials produced erratic fading rates on exposure to light. This phenomenon was attributed to either the occurrence of photochromism or the disintegration of the dye particles in the ink, but further testing needs to be conducted to gain a better understanding of this reaction. Other factors also influenced the light fastness of the ink jet materials, such as the type of paper employed for printing, ink concentration and ink combination. The electrophotographic printed materials were found to be more stable to light, although the yellow toner from some of the systems would show noticeable fading after approximately 65 to 325 years on permanent display (at 50 lux for eight hours per day).

A range of basic conservation treatments was also been investigated and the results indicated that ink jet print materials are very sensitive to all forms of

aqueous treatments. Finally, thermal/dark ageing has been performed on the digital printed papers employed in this investigation. The conclusion is that all of the papers are prone to yellowing in storage.

To Mum, Dad, Elaine and Jason
Thank you for all your help and support

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ABBREVIATIONS

ΔE_{94} – CIE94 colour difference formula (1994)

ΔE_{ab} – CIELAB colour difference formula (1976)

$\Delta E_{CMC(l:c)}$ – CIE formula for the calculation of small colour difference (1988)

AIC – American Institute for Conservation

ANSI – American National Standards Institute

ASTM – American Standards for Testing of Materials

BIJ – bubble ink jet

BJP – British Journal of Photography

BS – British Standards

C - Celsius

CCA – charge controlling agent

CGL – charge generating layer

CGM – charge generating materials

CI – colour index

CIE - Commission International de l'Eclairage

CIE94 – CIE colour difference formula (1994) for coordinates L*, lightness, C*, chroma, h*, hue angle

CIELAB – CIE colour difference formula (1976) for coordinates L*, lightness, a*, measures colour range red to green, b*, measure the colour range blue to yellow

CIJ – continuous ink jet

CMC (l : c) – CIE formula for the calculation of small colour difference (1988) using coordinates L*, lightness, C*, chroma, h*, hue angle

CMYK – cyan, magenta, yellow and black

CTL – charge transporting layer

CTM – charge transporting material

DOD – drop-on-demand

dpi – dots per inch

D(λ) – damage wavelength

EDS - Energy Dispersive X-ray Spectrometer

EH - Effective humidity

gsm - grammage

HP – Hewlett Packard

IAFADP – International Association of Fine Art Digital Printmakers

IMS – industrial methylated spirits

IPI – Image permanence Institute

IR – infrared

ISO – International Standards Organisation

ISVE - Inveresk Somerset Velvet Enhanced

JNF – just noticeable fade

klux – kilo lux hours

lux – lumens per square meter

M - mole

m –meter

mg – milligrams

ml - millilitres

mm – millimetres

N - nitrogen

nm - nanometers

OPC – organic photoconductor

pH - pouvoir hydrogène or 'hydrogen power'

PVC – polyvinylchloride

PVOH – polyvinylalcohol

RGB – red, green, blue

RIT – Rochester Institute of Technology

RH – relative humidity

SD – standard deviation

SDC – Society of Dyers and Colourists

SEM –scanning electron microscope

TLC – thin layer chromatography

UV – ultra violet

V – volts

v/v – volume per volume

Vol. -volume

W - watts

Whm^{-2} – watt hours per square metre

X – times (magnification)

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1.0 ABSTRACT

This research project has investigated the light fastness of ink jet and electrophotographic printed materials by the means of an extensive accelerated and natural ageing test programme. The effect of visible radiation of different wavebands on the deterioration of a selection of ink jet printed materials has also been assessed. The findings of the research indicate that all of the ink jet printed materials tested are sensitive to light and should not therefore, be put on permanent display. Most of the ink jet printed samples exhibited greater light sensitivity to the shorter wavelengths of the visible spectrum, than the longer wavelengths, with damage decreasing as wavelength increases. This relationship was not evident with the cyan and blue printed samples, which showed that their light sensitivity was determined by the spectral absorption characteristics of the printed patch. Some of the ink jet printed materials produced erratic fading rates on exposure to light. This phenomenon was attributed to either the occurrence of photochromism or the disintegration of the dye particles in the ink, but further testing needs to be conducted to gain a better understanding of this reaction. Other factors also influenced the light fastness of the ink jet materials, such as the type of paper employed for printing, ink concentration and ink combination. The electrophotographic printed materials were found to be more stable to light, although the yellow toner from some of the systems would show noticeable fading after approximately 65 to 325 years on permanent display (at 50 lux for eight hours per day).

A range of basic conservation treatments was also been investigated and the results indicated that ink jet print materials are very sensitive to all forms of aqueous treatments. Finally, thermal/dark ageing has been performed on the digital printed papers employed in this investigation. The conclusion is that all of the papers are prone to yellowing in storage.

2.0 INTRODUCTION

2.1 Content of research

Since the early 1990's, digital printing has introduced a revolutionary new way of working for the artist and photographer. Ink jet technology in particular, offers an efficient way of producing prints in a diverse range of sizes from A4 to many metres in length. The ink jet system can also print on a selection of media producing images with a variety of qualities that have great appeal to the photography and printmaking professions. Well known artists such as Jim Dine, Robert Rauchenburg, Chuck Close and David Hockney have all used and endorsed computer printers (primarily ink jet and electrophotographic systems) to produce art works. Institutions such as the Victoria and Albert Museum and the Tate Gallery, in London, Museum of Modern Art, in New York, the Art Institute of Chicago, to name but a few, have all acquired digitally printed artworks for their permanent collections. There has been little comprehensive research published on the durability of the produced work, in regard to both the ink and the substrate, because both technologies were originally designed to produce ephemeral text/graphics and proofs. There is now an urgent requirement for scientific research into the archival quality of the printed output (Glynn, 1998, Glynn 1999a, Glynn 1999b, Whale and Glynn, 1998).

The concept for this project was developed from an existing research project at Camberwell College of Arts, titled *The Integration of Computers within Fine Art Practice*, which has studied the use of digital printing combined with traditional printmaking techniques. The research found that ink jet printed materials were fugitive and had poor lightfast qualities that presented "serious shortcomings compared with the established printing media"[1].

The inks used for ink jet printing were generally dye based, with a water or water/glycol vehicle. Good lightfast inks were not necessary for the initial application. Hence, the inks had a much shorter display life than that of most traditional types of colour prints (Wilhelm, 2000). Since the adoption of ink jet printing by artists and photographers, manufacturers have introduced new inks and papers that have better archival stability characteristics, but this media still has many limitations in regard to light fastness (Lavery, Provost, Sherwin & Watkinson, 1998, Wilhelm, 2000).

Wilhelm Imaging Research Inc., an independent laboratory studying accelerated ageing, have published light fastness results for many types of ink jet printed materials (Wilhelm, 1999). The results cover a large range of different ink jet printing materials, but the fade limits are calculated using as *"easily noticeable fading limit, changes in color balance, and/or staining"* (Wilhelm, 1999), which is lower than the 'just noticeable fade' limit used in conservation research (Pretzel, 2000, Derbyshire and Ashley-Smith, 1999). The results are also governed by only one type of lighting exposure of 450 lux, which is above the museum standard of 50 lux to 200 lux. The ink jet printing manufacturers often publish image life limits of their branded media, but again the fading threshold used may not to museum standards, and the published light fastness graphs are printed with insufficient information and little detail on the testing conditions.

Light-induced fading of the coloured materials on objects is widely recognised as one of the most serious threats to their preservation because of the disfiguring and usually irrevocable alterations produced. Light, however, is essential if the object is to be viewed. Two characteristics of incident radiant energy that may be manipulated to reduce its degradation potential are intensity and composition (Bowman and Reagan, 1983). Previous research on the light ageing of sensitive dyes has found that the majority of fading was catalysed by wavelengths from the visible spectrum and the dyes were relatively untouched by the more damaging wavelengths of ultra violet radiation normally filtered out in museum conditions (McLaren, 1956). Museums and galleries, therefore, have to manipulate lighting conditions with the view to reducing the deterioration rate of the object while taking into account the aesthetic viewing requirements of the material on display.

2.2 Aims and objectives of the research

Light damage can occur over a period of several months or years. Therefore, accelerated light ageing tests are employed to speed up the photochemical reactions, in order to assess deterioration rates in the short term. Accelerated light ageing tests are a recognised method for predicting the light fastness of an object (Feller, 1990). The tests enable the conservator to identify materials that are sensitive to light, so that necessary precautions can be taken. In this investigation, an extensive light fast testing programme has been undertaken to monitor the deterioration rates of digital prints. The light-testing programme has taken into account the effect different papers and ink combinations/concentrations could have on the fading rate of the materials. Since artists and photographers have exploited mostly ink jet and electrophotographic printing processes in their work, the research has focused on selected manufacturers from these areas. Accelerated light fast testing has been criticised in the literature for not accurately duplicating the fading rates of materials (see 3.5.1 and 3.5.2), and the environmental controls employed in all of the tests investigated could not be completely controlled or monitored. Therefore, this testing programme has included the assessment of four different light sources, in order to assess any trends in the deterioration of the print materials and has also examined the regions of the spectrum that contribute to most of the fading reactions, using different types of light filters. From analysis of the results, recommendations for display conditions of this type of print have been made.

Objects can also be physically damaged by mishandling, inadequate storage, as well as the general deterioration that occurs over time. Such material requires interventional conservation treatments to stabilise its condition. A basic range of treatments used in paper conservation has been reviewed and their application to this type of material has been evaluated. Testing has been concerned with the detrimental effects that may occur with these treatments, such as: physical changes; loss of image and the substrate material; and changes in ageing characteristics after treatment.

Another accelerated ageing technique used in conservation research is dark/ thermal ageing. This process subjects objects to high temperature conditions in order to accelerate the degradation processes in organic materials. Although the focus of this research was to study how light effects ink jet and electrophotographic printed materials, an additional investigation was conducted to assess whether the papers supplied for the printing processes are of archival quality. Previous research on the stability of coated papers, supplied for ink jet technologies, found that the papers were prone to yellowing in ambient conditions caused by the presence of fluorescent agents and latex within the coatings (Mailly, Le Nest, Serra Tosio & Silvy, 1997).

[1] Barfield and Whale, 1997, p. 55.

3.0 OVERVIEW OF PUBLISHED LITERATURE

3.1 THE USE OF DIGITAL PRINTING BY THE FINE ART AND PHOTOGRAPHY PROFESSIONS

The use of computer printers to produce fine art prints really became established after Graham Nash, the rock musician, realised the potential of large format ink jet printers, in 1989 (Jürgens, 1999). He had been a keen photographer during his pop career and his interest led him to the area of computers and computer imaging. He investigated methods of high quality digital output and discovered the Iris 3047 (36 x 46 inch), which was able to produce high resolution continuous tone ink jet images, previously used for offset proofing. He started to use the machine to print his photographs on a variety of substrates, and then opened up a business called Nash Editions, in California to offer the services of the printer to other artists. To define these prints from ordinary commercial graphics the name Giclées was given to the produced work, which comes from the French word for 'spit' or 'spurt'. In the USA, this term has been used to refer to Iris printed materials in particular, and the name 'Iris Giclée' has been patented by Iris Graphics Inc., a division of Scitex, USA[1].

Development of sophisticated design and imaging software for the computer, along with the falling price of large format ink jet printers, meant that more and more artists begun to explore this medium (Barfield *et al.*, 1997, Miller, 1998a). Now the prints are appearing in exhibitions and collections all over the world and the technology is being taught in most art institutions. Well-known artists such as David Hockney, Robert Rauchenberg, and Jim Dine from the USA (Norville-Day and Jaques, 1998, Simpson, 1998), and Paul Colwell, Charlotte Hodes, Kathy Pendergast, Grenville Davy and Richard Hamilton from UK (Computers and Printmaking, 1999, Hamilton, 1998, Hall and Glynn, 1999), have all used ink jet technology to produce their work. The organisation the International Association of Fine Art Digital Printmakers (IAFADP)[2] was also set up in 1997 to promote digital fine art printmaking and to establish quality and print longevity standards for continuous tone ink jet printing. Many photographers have readily adopted the technology as it has many advantages over conventional silver halide photography (Gregory, 2000). Users of the technology regard ink jet prints, when produced on the appropriate media, as superior to silver halide prints[3], although light fastness is less than the average colour photograph, which lasts *ca* 12-15 years before noticeable fading by light occurs (Wilhelm, 1999).

Electrophotographic printing has also been adopted by artists to produce their work, although the technology has not made the same impact as ink jet printing has on the art world. Artists such as David Hockney, Mark Tansey, Ray Johnson and the photographers Carl Toth and Martin Parr have all produced xerographic artwork (Norville-Day, 1994, Norville-Day *et al.*, 1998, Lightfoot, 1995). Hockney considered the process as a new art form, an artist's tool to be explored further, and believes that an 'office' copy is as valid as traditional printmaking processes (Norville-Day, 1994, Lightfoot, 1995). He is also quoted in saying that the prints '*are not reproductions: but are very complex prints in the same way as a print is not a reproduction but is just itself.*'

Other digital printing technologies have also been adopted by artists and photographers such as dye sublimation, electrostatic, thermal dye transfer, for example, but these printers are much less popular than ink jet and electrophotographic systems.

3.2 INK JET PRINTING TECHNOLOGY

3.2.1 Introduction

The first commercial ink jet printer was introduced in 1979 using Bubble Jet Technology by Canon (Gregory, 2000), but the concept of the system was discovered much earlier[4]. Ink jet technology is a digital printing system that produces images directly onto paper from digital data or scanned images, without transferring ink with an image carrier. Ink jet systems rely on several streams of very fine uniformly shaped droplets of ink that are controlled by a digital electronic imaging source, to produce images directly onto plain or specially coated papers. The streams of ink are projected from the printer head, which scans the printing surface laterally and the paper is fed incrementally between the scans (Glynn, 1999a, Whale and Glynn, 1998).

The technology enables high quality photographic images to be printed on a wide range of substrates and in large formats up to seven metres in width[5]. Print quality and low cost are the major selling factors for ink jet printers and the systems have a high market potential due to their colour capability (Bauer and Ritter, 1996). Ink jet technology is also used for many other applications, for example, fabric and carpet printing, poster and billboard printing, bar code and sell-by date printing on packages and tins, postal addressing and coding, and wire/cable marking (Gregory, 2000).

Many factors contribute to print quality produced by an ink jet system. For coloured prints some of the more important factors are the vividness or brightness of the colours (chroma), resolution, number of grey scales, edge acuity and colour-to-colour bleed. Print durability characteristics also contribute to image quality such as light stability and wet fastness (Gregory, 2000). Resolution, normally quoted in dots per inch (dpi) or dots per millimetre (d mm^{-1}), and the number of grey levels are very important to print quality. Resolution is variable depending on the configuration of the dots that make up the image, and is known as the 'dithering pattern'. The dithering pattern is the most visible characteristic of the ink jet print and generally, can be seen with the naked eye. However, there is a threshold figure, beyond which the human eye cannot distinguish the dithering pattern. Tests have shown that photo-realistic ink jet printers having 1500 dpi resolution and 5 grey levels produce a continuous tone print perceived as equal to colour photography (Gregory, 2000).

Ink jet ink sets are usually composed of the subtractive primary printing ink colours cyan, magenta and yellow with the addition of black (CMYK), but recently other inks have been introduced to increase the gamut of colours printed, such as diluted magenta and cyan, orange and green. Different types of ink sets are also available for various applications such as photography, which requires a magenta that has a more bluish hue and a cyan that has a more greenish hue, to reproduce flesh tones more accurately.

3.2.2 The different types of ink jet printers

There are two distinct lineages within the ink jet family, they are Continuous Ink Jet (CIJ) and Drop on Demand (DOD) (see fig. 3.1)

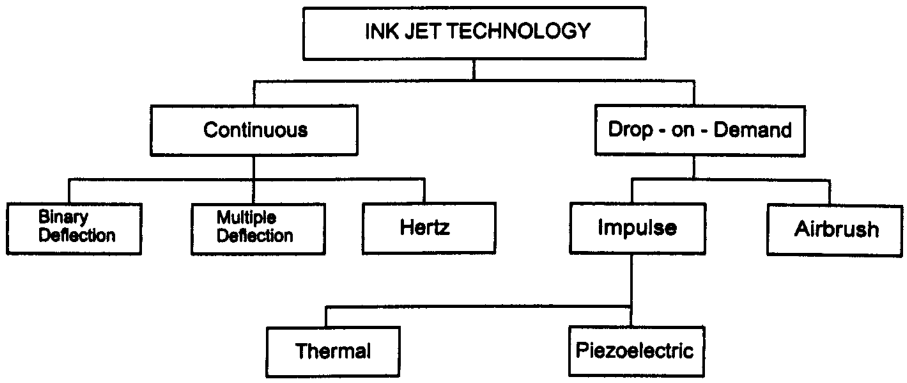

Fig. 3.1 The range of ink jet printing technologies.

3.2.2.1 Continuous ink jet printers

Continuous ink jet systems employ a continuous stream of ink that is ejected from a nozzle, typically 10 to 120 microns in diameter (Nixon, 1999, Whale and Glynn, 1998). The stream of ink is broken down into droplets (approximately twice the diameter of the nozzle) by the action of an oscillating piezoelectric crystal, a composite material that deforms under the action of an electrical current. This action generates capillary waves that cause the ink stream to break up into discrete uniformly shaped droplets. The ink is ejected from the nozzle at very high speeds, creating as many as 120,000 droplets per second (Nixon, 1999). The droplets are then given a selective charge by passing through an electrical field, so that they can be deflected from the stream to form a printed image. The charging of the droplet can be performed in three different ways:

- The Multiple Jet process applies a charge of varying degrees to each individual droplet. The droplets are then deflected according to their charge to form an image – the greater the charge, the greater the deflection and, therefore, the larger the printed image. Droplets given a small charge proceed into a catcher tube or gutter to be wasted or recycled (Thompson, 1998, Nixon, 1999).

- The Hertz process selectively charges the droplets so that the ink that has no charge passes through the electrical field undeflected to strike the substrate. The charged droplets are deflected by the electrical field and the can be discarded or recycled (Nixon, 1999, Thompson, 1998) (see fig. 3.2).

- The 'Single jet' (also known as the binary process (Nixon, 1999)) charges the droplets in the same manner as the Hertz system, but the deflected droplets are used to form an image and the uncharged droplets are passed onto a reservoir for disposal or recycling (Thompson, 1998, Nixon, 1999).

The Hertz technology is more suited to colour printing and the technology is employed by Iris Graphics Inc. (Intense Resolution Imaging Systems), who were the manufacturers of the Iris 3047, the first large format ink jet printer to be employed by fine artists (see 3.1). Iris, along with Calcomp, developed the first continuous tone (contone) ink jet printer, which produced high-resolution graphics by generating density variations using differing amounts of micro droplets placed in a given pixel. This can be varied from 1 to 31 droplets per pixel. Thus, the printed dot size can vary from about 25 microns up to about 500 microns (Allred and Schwartz, 1994). The Iris 3047 printer has a resolution of 300 dpi, but because the system can vary the size of each dot, the image produced can have an 'apparent resolution' of 1800 dpi. Iris has also introduced ink jet printers that now have an apparent resolution of 2400 dpi.

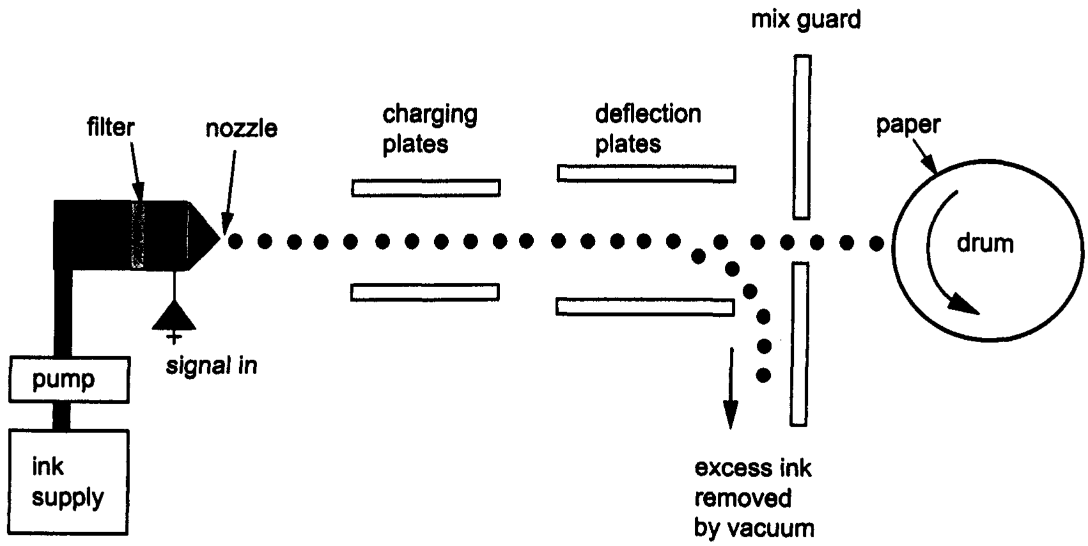

Fig. 3.2 Hertz continuous ink jet technology (Kenyon, 1996).

3.2.2.2 Drop-on-demand ink jet printers

DOD printers differ from CIJ ink jets in that they project droplets of ink only when required. In addition, the droplet is not charged, so there is no deflection involved, therefore, the droplet is ejected directly onto the desired point on the substrate. DOD printers use larger orifices than CIJ systems, typically 50 to 100 microns in diameter, and therefore can use pigmented based inks. DOD printers produce droplets that are approximately equal to the size of the orifice diameter (Whale and Glynn, 1998).

DOD printers are much cheaper to produce and maintain than the CIJ systems, but printing speeds are lower than CIJ. This is because of the effective droplet delivery rate depends on relaxation phenomena rather than on the streaming of ink from a pressurised jet. DOD printers disperse ink at rates of 0-4000 drops per second. DOD printers are becoming the dominant printing technology for low and medium speed printing because of their simplicity, low cost and high quality (Gregory, 2000). There are two different processes of DOD printers: airbrush and impulse.

- Airbrush systems use a solenoid that, when activated, withdrawing a plug to allow ink to flow into the print head. Air is injected into a narrow ink chamber, creating an aerosol, which is directed out of an orifice. This system produces low-resolution graphics (approximately 12 dpi) therefore the technology is restricted to producing super wide format posters and billboard images that are viewed from distance (Nixon, 1999).

- Impulse technology is another DOD printing process. This technology is divided into two different types: piezo and thermal (or bubble jet) printing.

- With piezo DOD printers (developed by Seiko Epson Corporation in the mid-1990's) (Gregory 2000), the droplet is ejected from an ink filled chamber contained in the print head. A pressure pulse is induced onto the chamber by the application of a voltage to an oscillated piezoelectric crystal. The crystal is made to deform in various ways, which are defined by the make of printer, and the force applied to the ejected droplet of ink. The crystal can be made to either bow, or be pushed, or in the 'shear' mode, one side of the crystal remains fixed while the other moves within the plane (Nixon, 1999, Kenyon, 1996). After the droplet has been ejected, a vacuum is created in the chamber, which fills up with ink, so that the process can then be repeated.

- Thermal DOD printers (also known as bubble jet printers (BJP)) employ a heating element at the tip of the printing nozzle that produces thousands of sudden temperature rises (300 °C – 400 °C) per second. These rapid increases in temperature cause a tiny bubble to form, which exerts pressure leading a single ultra-fine droplet to be ejected from the nozzle. Ejection of the droplet followed by the collapse of the bubble creates a vacuum as in the piezo system, drawing new ink to replace the ejected ink, and the process starts again (Nixon, 1999, Kenyon, 1996, Gregory, 2000). The entire process can be repeated several thousand times per second. The number of nozzles may vary, from a minimum of 50 to several hundred, to enable simultaneous printing of one or more lines of text. These types of printers are used in offices and homes to produce mid-range quality images. Canon and Hewlett-Packard are the main producers of thermal ink jet printers.

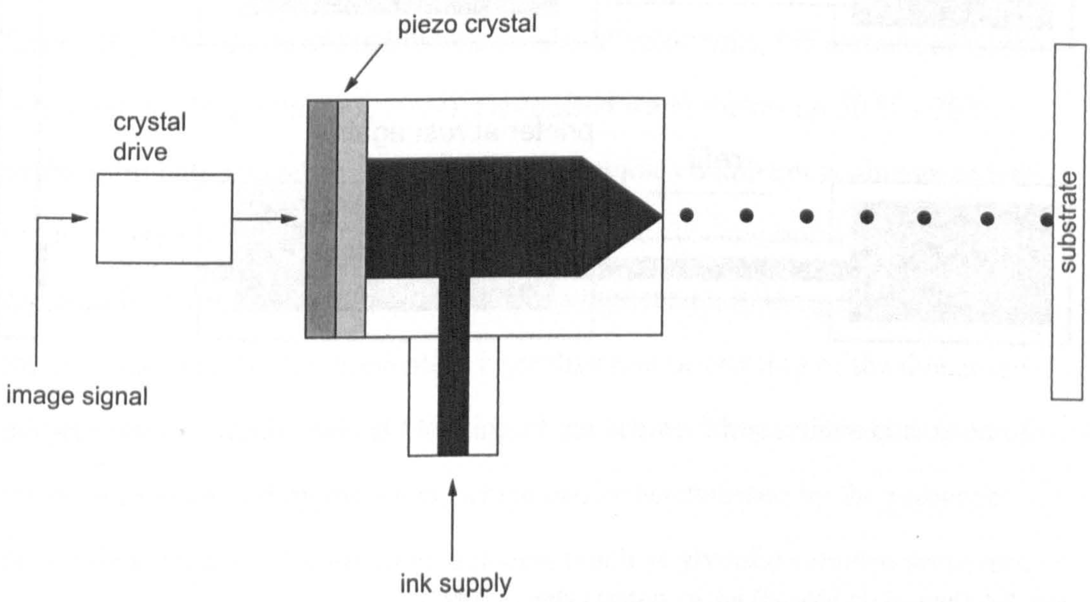

Fig. 3.3 Piezo ink jet technology.

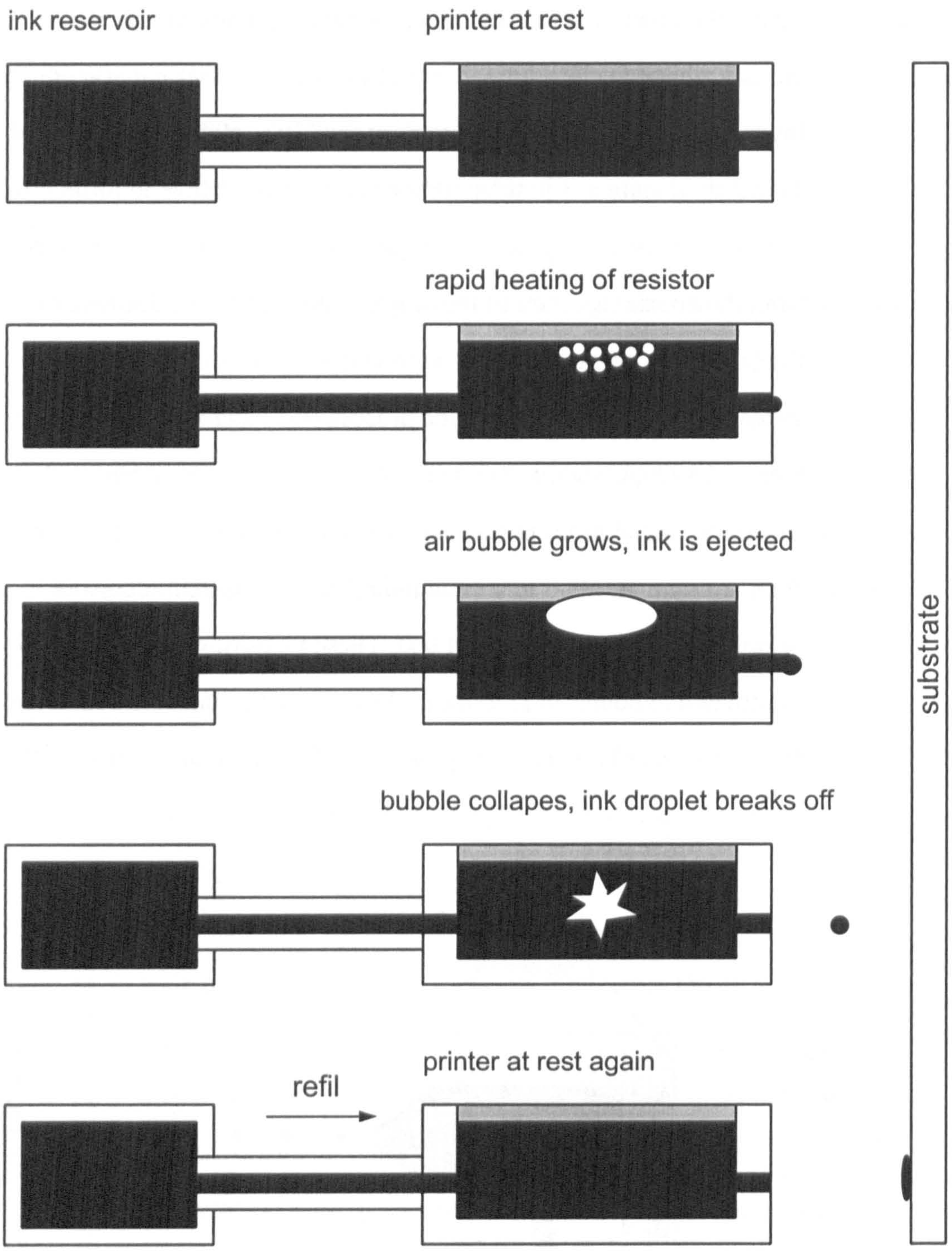

Fig. 3.4 Thermal (bubble jet) ink jet system (Jürgens, 1999).

3.2.3 Ink jet formulation

3.2.3.1 Introduction

There are three types of ink jet ink: aqueous, solvent and phase-change. Most of the systems use water-based inks that contain organic dyes (DOD, BIJ and Hertz CIJ printers). Solvent-based inks are used mainly with continuous printers for industrial use[6]. Phase-change inks are waxed based and are solid at room temperature, but can be ejected from a DOD print head when heated. The inks have better 'holdout' than water-based ink jet inks, and produce vibrant graphics on all substrates including transparencies. These printers have been used to produce art works, but the prints are more light sensitive and more expensive than ink jet images. The wax ink can also be easily damaged by surface abrasions, and the printers can only produce graphics up to A3 size (Kenyon, 1996). All of the printers investigated in this project use water-based inks, and the following has focused on this area of the technology.

3.2.3.2 Dye-based aqueous inks

Ink jet printers demand a specific type of liquid ink that must fulfil certain criteria. Generally, 5 % - 20 % of the ink will consist of colourants, the amount of which is termed 'loading' (Jürgens, 1999). De-ionised water makes up 50 % - 70 % of the formulation (Weber, 1991). A water-miscible co-solvent is always added to the ink: typically, a glycol[7] but pyrrolidones are also common. These solvents are used for various functions. They act as a humectant, helping to minimise the evaporation of water, preventing crystallisation or crusting of the dye at the ink jet nozzles, which leads to blocking of the orifice. They reduce corrosion of the print head caused by the water, which can be accentuated by the presence of certain electrolytes[8]. Certain co-solvents (such as glycols) can also serve as a biocide, as water promotes growth of micro-organisms. Co-solvents can also aid in controlling the viscosity and surface tension of the inks. Ink viscosity must be low so that it will not clog the nozzle during non-operating periods, typically 3-30 cP (Thompson, 1998). In certain cases, co-solvents can also improve the solubility of the dye, producing more stable inks. Glycol can be used as a penetrant as well, minimising the drop spread and drying time of the ink by reducing the content of the co-solvent. Separate surfactants are also added to increase the rate of penetration of the ink into the recording surface and to reduce drying time. Drying time of the ink is of great importance, as quick drying is more likely to improve adhesion and longevity of the printed image[9].

Other additives such as extenders (finely ground substances)[10] are added to the ink in order to modify its viscosity, to influence the jetting characteristics and to aid drop formation. Further additives can include such as 'modifiers' for surface tension and dye compatibility, anti-foaming agents, antioxidants, corrosion inhibitors, biocides, deodorants, chelating agents, and others (Jürgens, 1999). Light fading inhibitors can also be included, which allay the excess energy of the excited colourant molecules without the molecule changing structure or the bonds of the molecule being ruptured. The energy from the molecules is instead transferred to heat (Jürgens, 1999).

It is important for the ink to bond with the substrate to improve light stability, wet fastness and mechanical strength (Jürgens, 1999). The original water-based ink jet inks would remain very water-soluble once printed onto paper. This problem was overcome by using two methods: differential solubility; smelling salts. By modifying the pH value of the ink using carboxyl acid groups (Gregory, 2000, Thompson, 1998), it is possible to produce dyes that are soluble in an alkaline solution (where the group is ionised and confers water solubility), but have low-solubility on an acidic substrate (where the group is in its non-water soluble, non-ionised form). Water-based ink jet inks are normally given a pH value of 8-10, and most ink jet coated papers are neutral to slightly acidic with a pH value of 4-7 (Gregory, 2000). Dyes of this type are now used in several HP printers: they are based on the Food Black 2 structure (Kenyon, 1996).

Another method is ammonium carbonate or smelling salts (NH_4CO_3), derived from a weak acid, carbonic acid, and a weak base, ammonia. This salt is unstable in the ink and decomposes readily into gaseous components (water vapour, carbon dioxide and ammonia) once jetted onto paper. The decomposition of the salt produces the free carboxylic acid group and the dye becomes insoluble (Gregory, 2000). Other methods are being introduced that use 'zwitterions' formation between the protonated amino groups and the sulfonate groups[11].

Wet fastness of ink jet ink can also be improved using amides. Most dyes are anionic, but mono- and poly- functional amides form dyes with positive charges, know as 'cationic dyes'. Cationic dyes have a much higher water fastness than typical anionic dyes due to their increased interaction with the substrate (Orlenko and Stewart, 1997, Jürgens, 1999). A dye can also be bound to a polymer binder that has an affinity to cellulose, or the functional groups of the dye can be modified to make it attract to cellulose (Jürgens, 1999).

Aqueous-based inks were originally the only inks employed with high-resolution ink jet printing, because of the small diameter of the nozzles necessary for fine droplets of ink. Colourants suspended in aqueous binders, however, fade more quickly than do the same materials in oil media, which form protective films around the dye particles.

3.2.3.3 Continuous ink jet ink formulations

Continuous ink jet inks contain an electrolyte to give an electrical charge to the ink so that the ink droplets can be controlled during printing. These electrolytes are often by-products of the dye synthesis (Lyne and Aspler, 1984). Continuous ink jet inks have a high water content. The inks can also contain a base, wetting agents, and a blend of up to eight solvents that hold the colourant, binder and additives in solution (Thompson, 1998). The binders are polymeric and are selected to control viscosity and droplet formation, and to bind the colourant to the substrate. Additives may include conducting salts to ensure that the droplet will hold a charge (Thompson, 1998). Since the nozzles on the continuous ink jet are very fine, the systems must employ dye-based inks otherwise the print head can become clogged.

3.2.3.4 Piezo and bubble ink jet ink formulations

Piezo and bubble ink jet technology use a larger orifice for printing than continuous ink jet printers. Therefore, pigments and dyes based inks can be employed. Typically, dimensions of the particles are kept within 1/20 of the nozzle diameter, e.g. 1 micron for a 20 microns orifice (Jürgens, 1999). Both types of printers can be prone to drying during the quiescent period, therefore all ink formulations use glycol or other humectants to prevent clogging. Bubble jet dyes must also be thermally stable to prevent 'kognation', where decomposition products from the dye are deposited onto the heating elements of bubble jet print heads. Kognation (Japanese for biscuit) is promoted by impurities in the dye and can be prevented by incorporating sulfonic-groups in the dye molecule (Weber, 1991).

3.2.3.5 Basic requirement of dyes for ink jet inks

Ink jet dyes must possess several factors: good solubility; high optical density; good heat stability; good solubility of possible decomposing products; good wet and light fastness; purity; non-toxicity; they must not interact with other ink components and printer parts (Orlenko *et al.*, 1997, Jürgens, 2000). Initially, inks were developed from existing dyes used for textiles, paper and food, purified to a high standard for ink jet (Kenyon, 1996, Gregory, 2000). These dyes were found to have very poor light stability and wet fastness. By the selection of conventional 'acid', 'direct' and 'reactive' dyes, new forms of these dyes were subsequently developed with improved properties for ink jet applications[12].

Originally, only dyes were suitable for high-resolution ink jet printing rather than pigments because they are more transparent, have higher tinctoral strength, and provide a purer rendition of colour[13]. Most organic colourant are derived from the basic chromatic ring compounds benzene, naphthalene, or anthracene. Among the most important synthetic colourants for ink jet belong to the azo, phthalocyanine and anthraquinone classes[14]. Azo dyes are the most common dyes used with ink jet printing for all four ink colours, and can be both water and solvent soluble. The molecules of this class of colourant contain one or more azo groups (-N=N-); in addition water soluble azo dyes will have a sulfonic acid group ($-SO_3H$) (Jürgens, 1999).

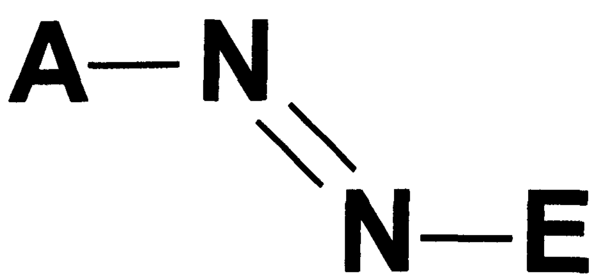

Fig. 3.5 General azo dye structure where both A and E are aromatic groups.

Table 3.1 Some typical dyes used in ink jet ink formulations (Clariant, 1997).

Ink Colour	*Dye Name*	*Chemical Class*	*Light Fastness (Blue Wool Scale 1-8)*
Cyan	Purified CI Direct 199	Phthalocyanine	7
Magenta	CI Acid Red 52 CI Reactive Red 180	Xanthene Monoazo	2 4
Yellow	CI Acid Yellow 23 CI Reactive Yellow 37	Monoazo Monoazo	4 – 5 4
Black	CI Reactive Black 31 CI Direct Black 154[15]	Disazo Copper Complex Ployazo	5 – 6 5

Other dyes that can be used for ink jet printing are CI Acid Red 249 (Kenyon, 1996), CI Direct Yellow 157, CI Direct Black 168[16], CI Direct Black 171[17] (Bauer and Ritter, 1995) and CI Acid Blue 9[18] (Gregory and Double, 2000).

Azo dyes tend to undergo oxidative reactions when printed on cellulosic, polyhydroxy coated or polyester substrates[19]. Azo dyes can also undergo reductive mechanisms when printed on protein substrates, such as gelatine, silk or wool but this is less common (Lavery *et al.*, 1998). The stability of a dye can be increased by the manipulation of the lifetime of the excited singlet state. Dyes with long lived excited singlet states tend to undergo photo degradation quite rapidly. By reducing the lifetime of the dye in the excited singlet state, photo stability can be increased (Lavery *et al.*, 1998). Radical scavengers and UV absorbers can also be added to either the ink or substrate (or both) to enhance light fastness (Gregory *et al.*, 2000). Dye manufacturers such as Avecia are trying to develop 'trichromat' dyes, which have low and equal fading rates.

3.2.3.6 Pigment-based inks

Pigment-based ink jet inks were originally used to produce outdoor posters and signs that required low resolution. Pigmented inks need a larger orifice so that the pigment particles do not block the ink jet nozzles. The larger orifice produces wider ink jet dots that are easily visible to the naked eye. Consequently, such inks were traditionally limited to producing posters and banners which were viewed from a distance.

Pigments, however, tend to have some advantage over dyes such as better image durability (including water fastness, rub resistance, and fade resistance), sharper edge acuity, and heat resistance (Orlenko *et al.*, 1997). A number of patents have been introduced in recent years that utilise pigment-based inks for DOD printers that do not clog the print head. The pigments are dispersed in aqueous inks using various methods, and include a resin in the formation in order to fix the pigment onto the substrate. A product of this type, using carbon black as the pigment, has now been commercialised by Hewlett Packard in their 1200C printer (Johnson and Belmont, 1995, Kenyon, 1996). Other inert pigments such as 'diarylide' yellows, metal salt reds, pthalocyanine blues, and monoazos have also been used (Kenyon, 1996, Clariant, 1997).

A few problems can occur with pigmented inks, such as rub and smear fastness on glossy coated paper, because the inks tend to lay on top of the media rather than blending with the substrate. In general, these inks do not produce prints as vivid as dye based inks, print 'gloss' can be lost, and pigment particless can aggregate to larger clumps, termed as flocculation.

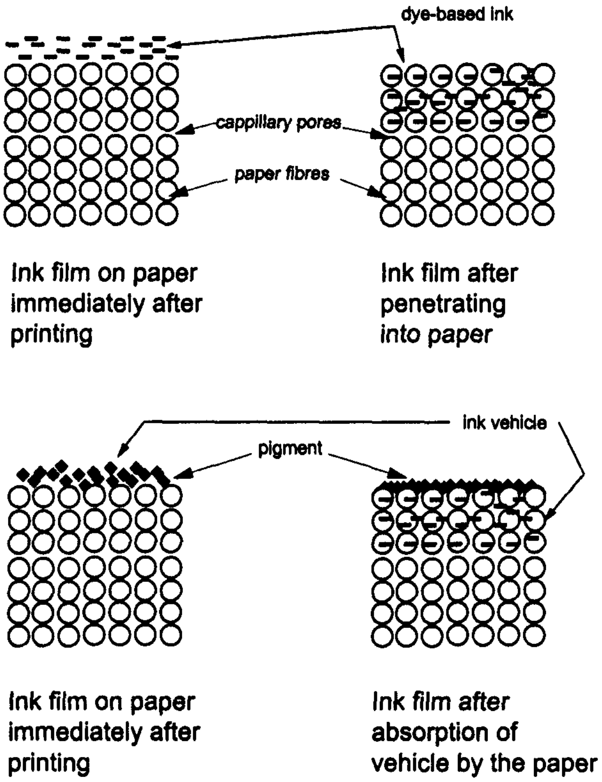

Fig. 3.6 Comparison between dye solution and pigment dispersion behaviours on paper.

Since pigments are insoluble in solvents and water, various methods have been introduced that enable the pigment to disperse into an ink vehicle. To prevent clumping, pigments are initially dispersed in solvents to aid their solubility in an aqueous medium, a process referred to as 'flushing' (Jürgens, 1999). Another method is to encapsulate a pigment particle in a resin. Surfactants or soaps are also used to disperse the pigments in either water or solvents. Pigments tend to produce opaque inks, which is undesirable for ink jet printing. To overcome this problem the refractive index of a pigment can be made the same as the vehicle it is suspended in, so that light can pass through the ink without being bent (Jürgens, 1999).

Dyes are dissolved in the vehicle (molecules typically less than a millionth part of a millimetre, 0.001 micrometres in size) whereas pigments (particles typically over one ten thousandths of a millimetre, 0.1 micrometres in size) are dispersed. Coloured compounds whose particle size lies somewhere between these are neither pigments nor dyes: they are known as 'colloidally dispersed pigments'.

Pigments can be ground down for ink jet use. Pigment particle sizes can range from 0.01 to 0.5 micrometres. Generally, the smaller the pigment particles, the better the colour, gloss, transparency, but the worse light fastness and further aggregation. If a pigment is too finely ground down, it could increase the viscosity of the ink, which would then affect flow characteristics (Bermel and Bugner, 1999, Glynn, 1999b, Jürgens, 1999).

A further method for developing colourants for ink jet inks is converting synthetic dyes into new pigments, by 'stacking' organic dyes to form larger particles. Water soluble dyes can be stacked like wet glass plates on top of each other, forming a crystal-like structure that precipitates out of an aqueous solution. The choice and order of the dye molecules is chemically manipulated to control the colour of the resulting pigment. The final size of the pigment crystal can be kept under control with the use of stopping molecules that fix onto the top and bottom of the stack. Some organic pigments also incorporate a metallic salt in their structure (Jürgens, 1999).

3.2.4 Ink jet coated paper

3.2.4.1 Introduction

The quality of an ink jet print is very dependent on the properties of the paper used for printing. For good quality output, a coating is employed with the papers to control the ink droplet. The coating enables the ink droplet to be maintained near the paper surface, in order to maximise colour density and contrast, while minimizing 'show through'. The coating is also designed to reduce ink-drying time, prevent wicking and to have a strong affinity to the ink for image permanence (water, light and mechanical fastness). Ink jet coated papers are also designed to be dimensionally stable, under going minimum cockle and curl during printing.

There is now a vast range of media available for ink jet printing. Ink jet papers can be divided into four basic groups of paper, plastic, paper-plastic combinations, and speciality media such as coated canvas (Jürgens, 1999).

3.2.4.2 Coating composition

Ink jet paper is designed to influence the rate of drying of the ink during the oxidative-polymerization phase. The surface of coated ink jet paper has a fine, highly porous structure allowing the rapid penetration of the ink vehicle into the image-receiving layer, so that the droplet's shape, size and location in the paper is controlled. The pores or capillaries in a coated surface are much smaller and more numerous than those of uncoated paper. Ink absorption is controlled by the coating formulation, which normally consists of silica - a fine hydrophilic material, which is transparent. Silica coatings are generally in order of 20μm thick and have void fractions of approximately 0.8 (Jürgen, 1999, Oliver and Jones, 1990, Lyne, 1988, Lyne *et al.*, 1984,). Matt coated papers typically have a 5 – 15 g/m^2 layer of silica/PVOH (polyvinylalcohol) applied to the surface of the paper (Lavery, 2000). Titanium dioxide and alumina can also be used. The limitations of these coatings are that only small amounts of binder can be added to hold the coating together and anchor it to the paper, otherwise void volume and hydrophilicity will be decreased. These ink jet papers can, therefore, be subjected damaged by surface abrasions. The binder is usually a combination of co-polymers that hold the active ingredients in dispersion. The most common hydrophilic binders used include polyvinylalcohol, polyacrylates, methylcellulose, carboxymethyl cellulose, and gelatine. Hydrophobic binders are also employed in latex form such as polyvinylchloride (PVC), polystyrene, and other polyvinyls (Jürgens, 1999).

Ink jet coatings can also consist of pigment (titanium dioxide), latex, optical brighteners and a dispersant. Common pigments added to the coatings are calcium carbonate and kaolin. The types of latex employed are radical terpolymers of styrene, butadiene, and acrylic acid. Fluorescent agents such as diamino-stilbene-sulfonic acid diluted in polyethylene glycol (Mailly *et al.*, 1997) are used in paper coatings. These brighteners absorb wavelengths between 320 nm and 400nm and emit between 410 nm and 500nm (peak approx. 450 nm - 460nm) (Popson and Malthouse, 1996) to make the paper appear bright white and to create good contrast between the substrate and ink leading to a wider colour gamut (Shearwood-Porter, 2000). The base sheet supporting the ink jet coating is made to be hydrophobic or at least well sized, to prevent the ink from penetrating into the base sheet.

Resin coated media contain a paper substrate which is coated with polyethylene on both sides. On the top-printing surface, titanium dioxide is suspended in the polyethylene layer, and then several aqueous coatings are applied over the top (see fig. 3.7). This type of paper is the most commonly used substrate for analogue photography (Kenyon, 1996), and is a very durable substrate capable of producing a high gloss finish (Lavery, 2000). The polyethylene layer is applied to the base surface to minimise curl of the paper during printing, or a thin aqueous layer can also be used (Lavery, 2000).

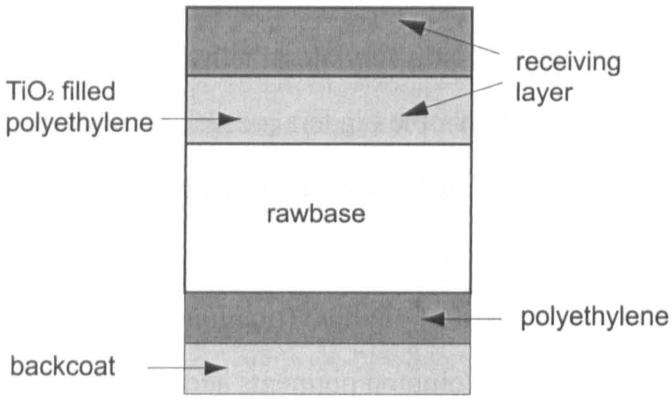

Fig. 3.7 Structure of a resin coated paper.

Photo glossy papers are composed of an aqueous receiving layer that can be applied directly to the base sheet or on top of a pigmented smoothing layer supported by a base substrate (Lavery, 2000). Some ink jet coated papers have used the coating technology developed for the photographic and traditional printing process (off-set, lithography, gravure). The pigmented layer can be composed of barium sulphate (10-30 micometres) suspended in a cross-linked gelatine binder (based on analogue photography), or contain a clay coating (based on traditional printing processes), but both types of surfaces can be subjected to cockling and curl if saturated with aqueous ink penetrates (Lavery, 2000). The most popular photo glossy papers employed for analogue and digital printing are based on polyethylene/resin coated substrates, with a hydrophobic barrier between the base substrate and the coating layer to prevent ink penetrating into the paper support and causing cockling (Lavery, 2000).

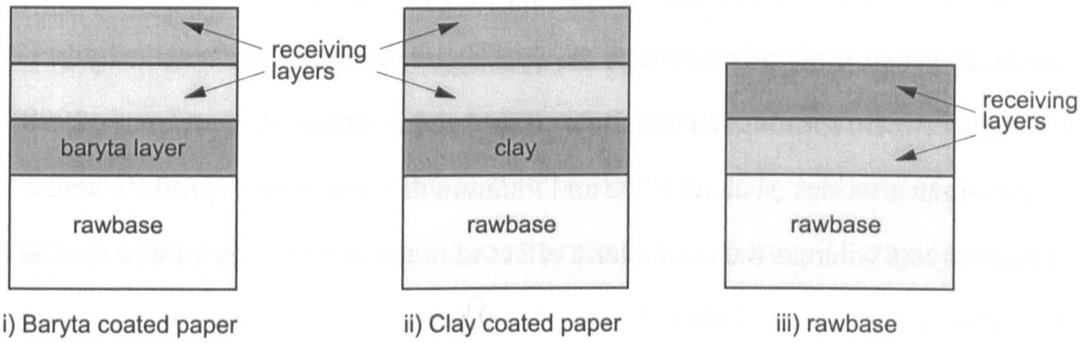

Fig. 3.8 Structure of different types of photo glossy papers.

3.2.5 Improving ink jet light stability and wet fastness

The light fastness of an image is not solely determined by colourant. The substrate is very important in determining whether a 'dyeing' is lightfast (see 3.4.3). Both physical effects and chemical effects are important. Thus, locating the dye away from the substrate surface and having it present in an aggregated form both enhance the light fastness of an ink jet image (Gregory, 2000). Mordants, such as cyclodextrin[20], can also be added to ink jet coatings to fix the dyes to the substrate and make the colourants more stable to light. The polymer binder, such as gelatine and poly hydroxy polymers, can also function as a mordant (Jürgens, 1999). Some of the additives used in the ink formulation to protect the chromophore[21], such as uv-inbitiors and antioxidants can be used in the media surface coatings at higher concentrations to influence the photo stability (Lavery *et al.*, 1998, Lavery, 2000).

The pH value of the substrate and ink can influence the wet stability of the printed image leading to crystallisation or aggregation on the dye particles on the paper surface, which can also improve the light fastness (Lavery *et al.*, 1998). When a dye crystallises on the surface of the media, the colourant is protected by the aggregation of the molecules into 'nanocrystallites', with the molecules at the surface protecting those trapped within the crystal. This can be observed for dyes with aqueous solubilities, which are pH dependent. The carbroxyl functionalised ink jet dyes behave in this way with the dyes aggregating in an extensive hydrogen bonded network, forming nanocrystals on the media surface (Lavery *et al.*, 1998). The inorganic oxides, such as silica and titanium dioxide, tend to produce acidic surface layers whereas the amphoteric effect of alumina produces a more neutral pH value (Lavery *et al.,* 1998). A high pH value tends to accelerate drying.

Metal complex dyes are very stable to light and are often used in ink jet printing. Copper phthalocyanine (used to produce cyan ink jet inks (see table 3.1)) and other metal phthalocyanine dyes are among the most stable dye chromophores (Lavery *et al.*, 1998). Metal cations increase light fastness by reducing the electron density in the chromophore making it less susceptible to oxidation and can protect the azo linkage of the dye molecules. (Lavery *et al.*, 1998). Use of metal cations, however, leads to a dulling of coloured chromophores, particularly the maganta dyes (Lavery *et al.*, 1998, Lavery, 2000). Many black dyes used in ink jet printing are metal complexes containing Cu^{2+}, Cr^{3+} or Co^{3+}. By coating the surface of the media with transition metal cations, the photo stability of dyes can be increased. Unfortunately, the resultant transition metal complexes can often cause slight discolouration of the media with consequent dulling of the image. (Lavery *et al.*, 1998).

3.2.6 Ink jet printing on traditional uncoated papers

Uncoated papers absorb the liquid ink jet ink through capillary action. The ink vehicle is drawn into the capillaries or inter-fibre voids in the paper structure, which leads to feathering/wicking, loss of ink density and image quality is impaired. In addition, larger dots are formed on the paper, which results in a loss of print resolution (Whale and Glynn, 1998).

Traditional printmaking and watercolour papers such as Somerset Velvet and Arches Cold Press have been employed for a majority of fine art ink jet printing. Many artists prefer to use traditional uncoated papers for ink jet printing because they are good quality papers with a heavy weight suitable for framing[22], they produce less graphical images creating softer lines caused by wicking of the ink, and the papers help to distinguish fine art prints from commercial graphics (Whale and Glynn, 1998).

Previous research has shown that, generally, ink jet inks give better light fastness results when printed on uncoated papers than on the coated ink jet papers (Wilhelm, 1999, 2000, Gillet, 2000) (also see 3.7.4). This was attributed to the uncoated papers allowing the dyes to diffuse into the substrate, which helped the chromophores to be protected from exposure to light. The papers also allowed the inks to mix of on the paper surface, which permited hydrogen bonding between the inks and the cellulose substrate.

3.2.7 Ink jet coated 'fine art' papers

In the last two to three years, a new form of ink jet coated paper has been introduced that looks and feels like a traditional fine art uncoated paper. With the rapid uptake of ink jet printing with the fine art professions, manufacturers such as Inveresk (Shearwood-Porter, 2000) and Hanhemuhle (Image Reports, 2000) have developed specialist papers for this market that have the qualities of a fine art paper but contain a non-visible coating, to control the ink droplet improving colour saturation and image definition. This research has investigated one such paper, Inveresk Somerset Velvet Enhanced, with the testing program (see table 4.1).

3.2.8 Lamination

Ink jet prints can be laminated by over-laying the image with a polymeric coating that contains an UV absorber. The lamination improves the light fastness of a print by preventing moisture and oxygen from coming into contact with the colourants (Jürgens, 1999). Since the process can affect the appearance of the final print, lamination tends to be used for industry and business graphics and not for images produced by artists and photographers.

3.3 ELECTROPHOTOGRAPHIC PRINTING TECHNOLOGY

3.3.1 Systems

Electrophotography is a process in which an image can be reproduced, by means of electricity and light. 'Xerography' or 'xeroxography', derived from the Greek word for 'dry writing', was developed out of the original inventions by Chester Carlson, in 1938 (Gairns, 1996). In 1950, the first commercial xerographic equipment was launched. Electrostatic print mechanisms are the leading technology for office copiers and printers. Main manufactures are Canon, Kodak, Agfa, Xerox and Minolta.

Xerography is based on forming electrostatic images by photoconductive discharge of an electrically charged surface. A uniform electrostatic charge is given to a photoconductive layer, called the 'photoconductor'. This layer is selectively discharged by exposure to light. The photoconductor traditionally consisted of a drum coated with selenium, but has been replaced with an Organic Photoconductor (OPC) system (Thompson, 1998, Gregory *et al.*, 2000). The light causes the charge in the 'dark' areas (text and/or images) to be dissipated, and the 'white' (non-printed) areas on the document to retain the charge, this image at this stage is referred to as the 'latent electrostatic image' (Thompson, 1998, Gregory *et al.*, 2000). A fine resin coated pigment, referred to as 'toner' (see 3.3.2) that has the same charge as the background, is then directed at the latent image and is repelled into the uncharged 'dark' areas. The image is then transferred onto a positively charged sheet of paper, and is fused onto the paper by heat and/or pressure. The photoreceptor is then cleaned to remove any toner residue so that the next image can be copied. The colour photocopier works by building up an image from four passes using the subtractive printing primary colours CMYK.

OPCs are dual layer devices composed of a thin (around 0.1-1.0 micrometres) charge-generating layer (CGL) on top of a thicker (around 20 micrometres) charge-transporting layer (CTL). The CGL consists of pigments (charge generating materials (CGMs)), and the CTL incorporates electron-rich organic compounds (charge transporting materials (CTMs)), that are usually colourless or slightly coloured (e.g. pale yellow) (Thompson, 1998, Gregory *et al.*, 2000). When light is directed onto the OPC it passes through the CTL layer and upon striking the CGL, it forms an ion-pair complex. The electron passes through earth and a positive hole is left which is transported to the interface. A variety of organic pigments have been used for charge generation including polyazos, perylene tetracarboxydiimides, polycyclic quinines, phthalocyanines and squariliums. Almost all modern laser printers use titanyloxy phthalocyanine, type IV polymorph, as the CGM (Gregory *et al.* 2000).

There are two different types of electrophotographic systems: the photocopier and the laser printer. Each system is defined by the method of expose used to form an image on the photoconductor plate. There are other printing systems available, as well as electrophotography, that are toner based. The main systems are 'electrography', ion deposition, electrostatic and 'magnetography' (Thompson, 1998).

3.3.1.1 Photocopiers

There are two methods of exposure used in photocopiers, which refer to the type of photoconductor employed. The original method uses a flatbed photoconductor, which allows a whole document to be copied in a single flash exposure, for high-speed output (see fig. 3.9). In modern photocopiers, the photoconductor is made of a flexible material, which is formed into a belt (Gairns, 1996). The more common method of exposure uses a photoconductor drum, where the image is illuminated and projected onto the plate receptor with a series of scanning lenses and mirrors.

3.3.1.2 Laser printers

The laser copier uses scanning laser radiation, controlled by a computer, to destroy the static charge of the photoconductor. In modern printers semiconductor lasers (light emitting diodes (LED)) are used (Thompson, 1998, Gairns, 1996). These printers are small, very reliable, highly efficient and readily manufactured at a low cost. The laser light scans a photoconductor drum. By switching the laser on and off at high-speed, the laser can transfer an image onto the drum by discharging the photoconductor surface. A rotating polygon mirror is used to direct the laser beam across the photoconductor surface and the high-speed switching of the semiconductor lasers allow a high-resolution pattern to be produced (see fig. 3.10)(Gairns, 1996).

The improving image quality (printers produce images made up with a series of pixels, with resolutions ranging between 300 and 600 dpi (Gairns, 1996)) and the fact that the printer can talk directly to a computer has resulted in an increased use of the laser copier as a high quality print engine for black and white text from the computer.

3.3.2 Electrophotographic toners

Toners comprise of a solid mixture of coloured toner powders suspended in thermoplastic resins. Typical composition consists of 90 % - 95 % resin (polyester, or copolymers of styrene, acrylics, or methyl- or butyl-methyacrylates, or epoxies); 3 % - 5 % colourant, 1 % - 3 % charge control agent (CCA); other additives such as dry lubricants and cleaning agents (zinc stearate and silicone oil) (Baur and Macholdt, 1995). Most companies are turning to polyester resins, as they have better fusibility than the other earlier resins. Polyesters resins are the most prevalent in full-colour application, as they have desirable properties such as pigment dispersant ability (Gairns, 1996).

Toners can be either dry or a liquid. Dry toners use particles with a minimum size of 5-10 micrometres, any less and the particles are prone to drifting into the atmosphere (Thompson, 1998). For high-speed printing, the toner is composed from a fine powder (5-25 micrometres in diameter) mixed with larger beaded material (200 micrometres in diameter), referred to as the 'carrier' (Thompson, 1998). The carrier is often made of iron or iron oxides and is surface coated in order to modify its charging properties. This is then agitated with the toner powder, creating a triboelectric charge. As the carrier maintains an opposite charge to the toner, each carrier bead is coated with an even distribution of small toner particles. When the developer is allowed to cascade over the photoconductor surface, only the areas where sufficient field strength exists are the toner particles attracted away from the carrier bead. This ensures that any stray toner particles landing in the areas of low field strength are re-attracted by the carrier beads (Gairns, 1996). Liquid toners are composed of particles dispersed in an insulating hydrocarbon or light mineral oil, and the dispersing process charges the toner particles (Gairns, 1996). Liquid toners enable particle size to be much smaller than dry toners and are used in finer resolution laser printers.

3.3.2.1 Toner colourants

The colourants used in toners can provide two functions: colour and control of the electrostatic charge of the toner particles. A variety of organic pigments are used for electrophotographic toners, including azo compounds (the basis for yellow pigments), quinacridone/xanthrene compounds (the basis for magenta pigments) and phthalocyanines compounds (the basis for cyan pigments) (Thompson, 1998, Gairns, 1996, Freeman and Sokolowska, 1999). Other types of organic pigments are also continually being introduced for toners[23]. The black pigment used in electrophotographic toners is generally carbon black (Gairns, 1996).

Coloured pigments are selected for their resin compatability/dispersabiltiy, heat stability, and light stability. They are characterised by their ability to change from a hard brittle state to a soft flowing state as they pass through their glass transition temperature, mostly commonly between 65 °C to 70 °C (Gairns, 1996, Thompson, 1998). Dyes are also employed with toners but not for their ability to deliver colour, instead they are used because of their electrical properties such as photoconduction and electrostatic charging of toners (Thompson, 1998, Freeman *et al.*, 1999). Since dyes are coloured, they are generally employed in black toners (Thompson, 1998, Gairns, 1996).

3.3.2.2 Charge control agents (CCAs)

The type of charge of the toner (negative or positive) depends on the photoconductor used and whether it is employed in a copying or laser printing process. Most toners rely on triboelectric charging, where two dissimilar materials are brought into frictional contact, and an electrical charge of opposite polarity is developed on each. The negative charge control agents comprise of organic molecules such as sulfonic acids, carboxylic acids, and their salts (Thompson, 1998). Complexes of azo dyes with ions such as chromium (Cr^{3+}) or cobalt

(Co^{3+}) can also be used, but are restricted to black toners because of their colour (Thompson, 1998)[24]. Delocalised organic molecules are used for positively charged CCAs and are based on mixtures of compounds containing highly acrylated phenazines (Thompson, 1998). Nigrosine dyes are the most important type of positive charge agent for black copies (Freeman *et al.*, 1999).

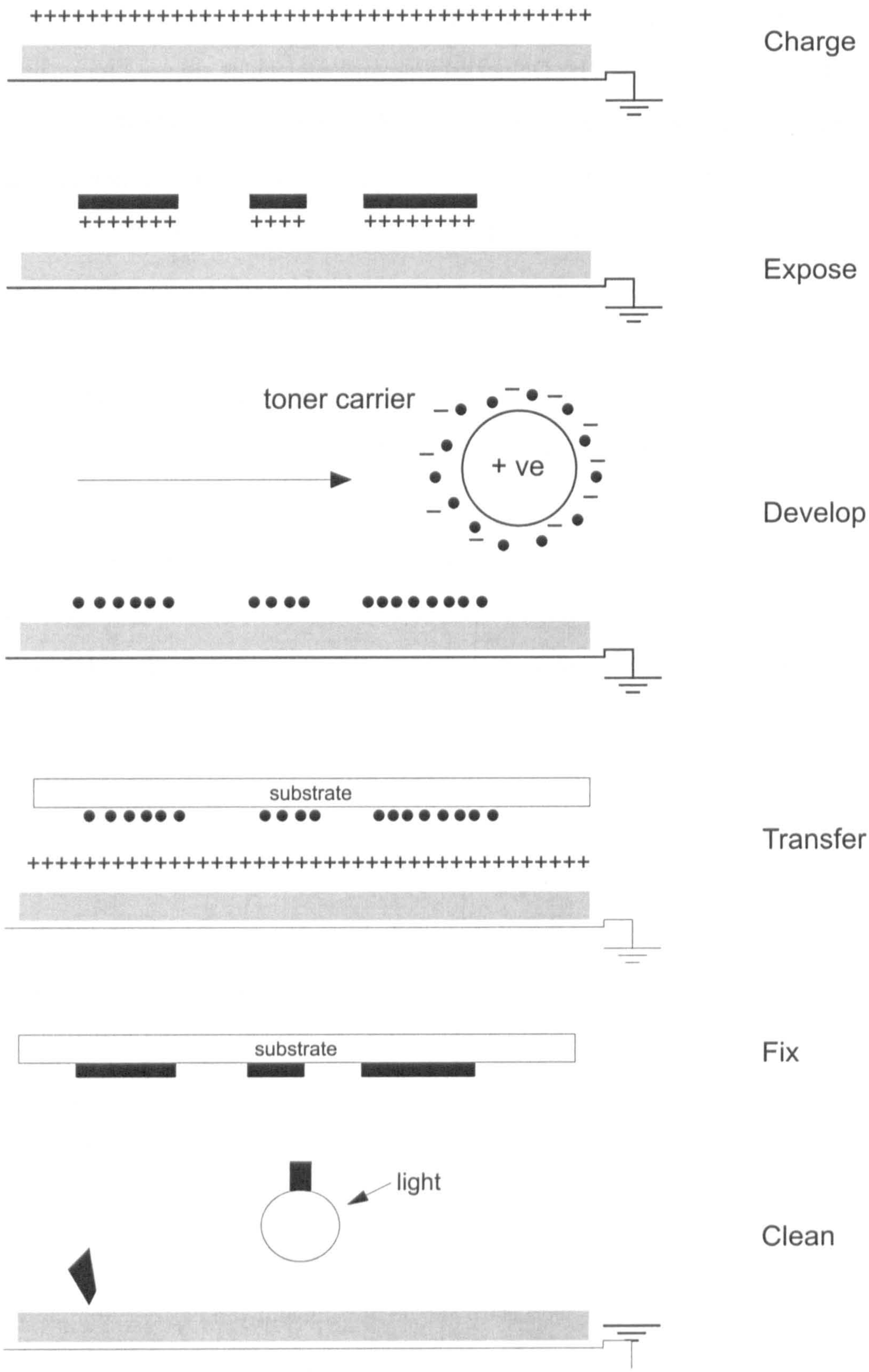

Fig. 3.9 The electrophotographic process steps (Gairns, 1996).

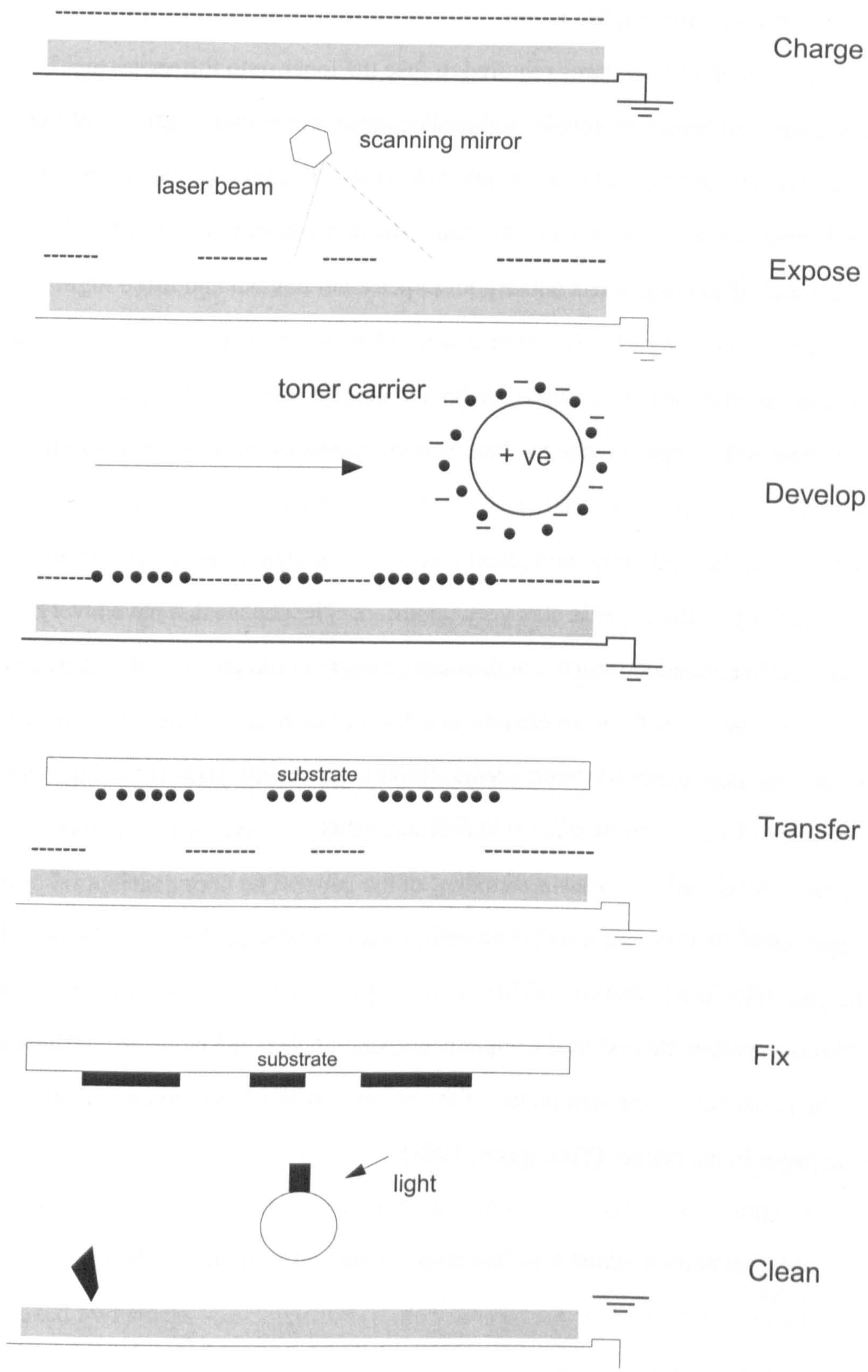

Fig. 3.10 Reverse development, the basic electrophotographic process employed in laser printers (Gairns, 1996).

3.3.3 Electrophotographic media

Due to the high temperatures required to fuse the toner onto the paper, the substrate must be dimensionally stable. Therefore, the moisture content of the paper must be maintained to a low level of around 5 % (+/- 0.5 %) otherwise, inadequate fusion of the toners can occur. The paper smoothness must be controlled. If too low, it can cause poor paper-toner contact and if too high, electrostatic sticking of the toner can occur (Thompson, 1998). The paper must not release filler or fibres, which can lead to contamination of the rollers, belts and fuser roller wipe. Sizing can help prevent the paper from contaminating the printing system, but certain sizes such as starch can cause poor adhesion of the toner. Instead, polyvinyl alcohol or styrene maleic is used. The electrical conductivity of the paper is also very important. The paper must have a very low electrical conductivity (or high conductivity) to hold electrostatic charge and facilitate toner transfer from the imaging drum (Thompson, 1998). If conductivity is too low, poor toner adhesion occurs. If too high, sheet-to-sheet sticking can occur and cause paper misfeeds (Thompson, 1998). Conductivity can also be affected by changes in moisture content of the paper. The fibre distribution of the paper must also be considered. The grain direction of each sheet of paper should be parallel to the path of travel in the printing system to give maximum rigidity. This means that the curl of the paper is perpendicular to the paper path. Therefore, if the paper curls after heat fusion of the toners it is less likely to cause jamming of the paper in the printer (Thompson, 1998).

3.4 ACCELERATED LIGHT AGEING

3.4.1 Introduction

In the case of organic materials, 'light' is considered to be the most damaging environmental factor leading to irreversible chemical changes. The reaction initiated by light is termed photo-degradation. The extent of the deterioration depends on: a) the intensity of the radiation; b) the time of exposure; c) the spectral characteristics of the radiation; and d) the fundamental capacity of the individual material to absorb and be affected by radiant energy. Deterioration can vary from slight loss of colour or embrittlement, to complete disintegration of the material.

3.4.2 Review of photochemistry

'Light' forms a small part of the electromagnetic spectrum. This ranges from longwave radio waves to gamma rays. Visible radiation, or light, occupies that part of the spectrum that possesses wavelengths from 380 nm (violet) to about 780 nm (red), but often the range is quoted as 400 nm to 700 nm. Beyond the red end of the visible spectrum lies the infrared (IR) with wavelengths between 780 nm to 1 mm. Electromagnetic radiation with wavelengths shorter than 100 nm to 380 nm is termed ultra violet (UV) (Thompson, 1998, Sinclair, 1997). Within the museum context, only UV radiation of wavelengths between 300 nm to 400 nm is of concern (termed near UV).

Electromagnetic radiation, including light, is a form of energy. A quantum of light energy is termed a 'photon'. The energy possessed by a single photon may be expressed by Planck:

$$E = hv \qquad (3.1)$$

Where v is frequency and h is a constant, known as Planck's constant. Photochemical effects can be initiated by the UV[25] and visible regions of the electromagnetic spectrum. IR radiation, however, does not cause photochemical reactions but may speed up any existing changes due to its heating effect (see 3.4.5).

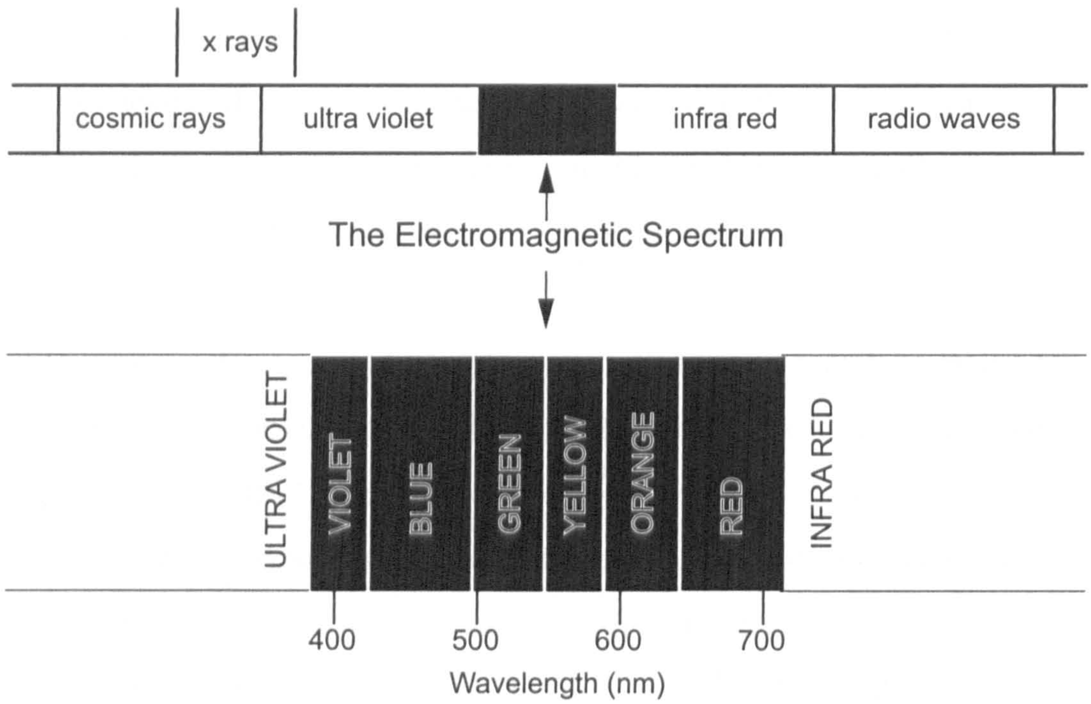

Fig. 3.11 The Electromagnetic spectrum

When light is incident upon a surface of an object, it can be reflected, absorbed, scattered and/or transmitted, depending on the properties of the system. For a photochemical reaction to occur, light must be absorbed by the object. This is the first law in photochemistry and is known as the Grotthus-Draper Law (Brill, 1980, Owen, 1980).

When a molecule absorbs the energy from a photon, the energy excites or 'activates' the electronic structure of the molecule. The electrons displace from a ground state into an 'excited state' (see fig. 3.12). Once activated, excess energy needs to be dispelled. This can occur in a variety of ways[26], one of which is that the molecule in its excited state reacts with other materials in the vicinity, for example, the substrate and other molecules such as oxygen or water. This later reaction (the secondary processes of photochemistry or *post-irradiation effects*) can start a chain of chemical events and are the cause of most of the photo-degradation in a system. Light can only be absorbed if it carries precisely the right amount of energy to promote an electron from ground state to an excited state.

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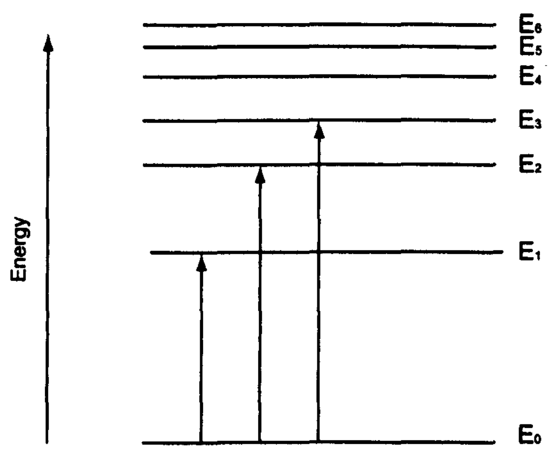

Fig.3.12 Some possible transitions to excited states for an atom that initially is in the ground state.

3.4.3 Photo-degradation of dyes

Dyes tend to be particularly sensitive to light. A photo sensitive dye has an excited state that chemically reacts while getting rid of the absorbed energy. But dyes have low quantum efficiency[27]; therefore the number of photons needed to fade a dye molecule is very high. The deterioration process of the molecules initiated by visible light leads to either one of the following reactions: photooxidation[28]; photoreduction[29]; phototendering[30]. If UV radiation is removed, photoxidation is the most common pathway followed in the degradation in the dyes, fibres and other organic materials (Brill, 1980, Owen, 1980, Giles and McKay, 1963).

The substrate has a marked effect on the light fastness of a dye, due to the influence of both chemical and physical factors. Fading reactions occur on the dye-air interface, because generally, the fading of a dye in a fibre depends on the presence of oxygen and water. The rate of fading of one dye may not be the same as it is for other dyes, but most dyes in the presence of a fibre, fade at an apparent first-order rate (Brill, 1980, Giles and Forrester, 1980). This rate of fading refers to where there is a rapid initial loss of the smaller molecules of the dye situated at the dye-air interface. Due to their size these molecules react more readily with light. This fading rate steadily decreases with time as all the smaller molecules react with light until only the largest particles are left, which are more stable to light energy (Brill, 1980, Giles *et al.*, 1980).

Dyes exist in the form of aggregates or crystals and the state of aggregation of the dyes has an appreciable influence on the fastness to light. Generally, the larger the size of the particles, the higher their fastness to light (Giles *et al.*, 1980, Beek, 1966, Baxter, Giles, McKee and Macauley, 1955). Organic pigments behave like dyes when exposed to light, but tend to be more photochemically stable, due to the fact that they are made up of larger sized particles, which are more resistant to light damage (Giles *et al.*, 1980, Beek, 1966).

3.4.4 Photo-degradation of paper

Light, particularly UV radiation, is also destructive to paper. Paper can become yellow and/or bleached, and can lose its strength (Erhardt, Tumosa and Mecklenburg, 2001, Havermans and Dufour, 1997, Havermans, 1995, Grattan, 1980, Brill, 1980). The sensitivity of paper to light varies and is determined by its composition, the type of sizing used and any impurities it contains. Exposure to light seems to also cause a long-term activation of the paper fibre. When a sample is removed from light, it continues to react with its moisture content, oxygen and decomposition products, and degrades at a faster rate than if it had not been exposed in the first place. This is due to the presence of peroxides that build up on exposure (Erhardt *et al.*, 2001, Daniels, 1986, Grattan, 1980, Brill, 1980).

3.4.5 Other factors that contribute to photochemical reactions

Other environmental factors such as atmospheric humidity, temperature and the presence of air-borne pollutants can affect the rate at which a photochemical process takes place. High humidity levels leads to swelling of the cellulose fibre and thus enables air to penetrate the intermolecular pores more readily (McLaren, 1963). Pollutant gases such as ozone (O_3), nitrogen oxide (NO), nitrogen dioxide (NO_2) and sulphur dioxide (SO_2) can induce and accelerate fading reactions caused by oxidation (Whitemore, Cass and Druizik, 1987, Whitemore and Cass, 1988, 1989, Zinn, 1994, Simon and Cass, 1993, Thomson, 1986). Temperature rises increase the agitation of atoms and molecules in a system, and can influence fading reactions by accelerating the diffusion of either oxygen or water vapour or both (Feller, 1964).

3.4.6 Spectral distribution of various light sources

Spectral distribution of a light source can have a strong influence upon the fading rate of a material (Saunders and Kirby, 1994, Cuttle, 1988, Kenjo, 1986). For an object to fade, light needs to be absorbed by the material. Light can only be absorbed if the energy of the wavelengths matches the energy required to displace the electrons to a higher energy level (see fig. 3.12)[31]. If the wavelengths that initiate photochemical reactions within a colourant are not present or their presence is diminished, the fading rate of the colourant can be slowed down. The spectral dependence of fading is important for museums and galleries because the spectral energy distribution of a light source is to a certain extent controllable. In addition, all museum lighting guidelines are merely stated in lux-hours, which is a measurement that does not incorporate the total output of a light source.

Russell and Abney in the 1880s were the first to document that different light sources affect the rate of fading of artists' pigments (Brommelle, 1964)[32]. Much later in the 1950s, Harrison (1950) found that low-quality paper exposed to radiation of different wavelengths suffered various degrees of degradation. He found that damage decreased with increasing wavelength, and introduced the idea of the damage factor, D (λ)[33]. The purpose of this factor was to find a relationship between damage and wavelength for the paper. Due to the complex nature of museum objects, however, he stated that it was impossible to allocate a damage factor for all materials. Thompson (1980) and Michalski (1987) also agreed with his conclusion that the damage factor relationship was limited.

McLaren (1956) has also investigated the effect of wavelength on the light fastness of dyes. He separated the visible spectrum into three regions: 400 nm - 460 nm, 460 nm - 600nm, and > 600 nm. His research led to the conclusion that, generally, light fast dyes were more affected by UV radiation and that light sensitive colourants were affected more by the visible region of the spectrum.

A more thorough investigation was conducted by Saunders and Kirby (1994) on the light fastness of artists' pigments. Using seven broad-band interference filters, the spectrum was separated into regions of approximately 100 nm width from 350 nm - 750 nm. Their research led to the conclusion that the inverse relationship of damage and wavelength was limited to the absorption characteristics of the colourant. The inverse relationship occurred for the yellow and red pigments selected for exposure, but for some of the blue pigments tested, and the blue wool dyeings 1-3, it was found that the shorter wavelengths did not fade the colourants as much as some of the longer wavelengths in the visible spectrum.

Research on the fading rate of colour photographs by Wilhelm and Bower (1994) contradicts the above finding. They found that "*different light sources produced very similar fading rates even though the spectral distribution of sources are very different*"[34]. They believed that for modern colour print material, the spectral distribution of the illumination source has relative little effect on fading rates. Far more important is the intensity of the illumination. However, recent research published by Wilhelm's company *Wilhelm Imaging Research Inc.*[35] discusses the use of different light sources to accelerate the ageing of digital print materials.

3.5 ACCELERATED LIGHT AGEING TESTS

3.5.1 Overview of test methods

Accelerated light ageing tests are based on the 'reciprocity principle', where photochemical damage can be measured by the quantity of light illuminating the object, times the length of exposure (lux-hours x time). Light damage can take many years to occur. Therefore, if illuminance is increased, the amount of time required to develop the same degree of fading is reduced. This form of testing, however, has come under much criticism in the conservation literature, because the process of photochemistry is influenced by many variables other than light

(Feller, 1990, Michalski, 1990). Previous research has shown that accelerated light testing can fail to predict the fading rate of materials (Saunders and Kirby, 1996, Wilhelm *et al.*, 1994, Thompson, 1986). One of the main reasons for failure is associated with the break down of the reciprocity principle (see 3.5.2).

3.5.2 Reciprocity failure

Reciprocity failure has been found to occur with light exposures of over 10 klux (Saunders *et al.*, 1996)[36]. The break down of the relationship between intensity and time is attributed to the depletion of oxygen during high irradiance (Wilhelm *et al.*, 1994, Whitemore, 1999, Saunders *et al.*, 1996). Oxygen is necessary for fading reactions to occur with organic materials (see 3.4.2). Another possible contribution is that the rapid exposure can create high concentrations of intermediate compounds that can react together in ways not attainable at the lower concentrations produced at low light intensities (Feller, 1994). Low humidity levels in the testing environment may further hinder reactions by the reducing the availability of oxygen (Wilhelm *et al.*, 1994, Saunders *et al.*, 1996).

High intensity light fastness tests can be expected to produce less overall fading, than the equivalent light exposure spread out over months and years of normal display (Saunders *et al.*, 1996, Wilhelm *et al.*, 1994, Gillet *et al.*, 2000). Wilhelm and Bower (1994) found in their research "*that most colour (photographic) materials exhibit at least some 'reciprocity failure' in light fading or light-induced stain formation in high-intensity, short term tests, even though the total lux hours, temperature and relative humidity are the same*"[37]. They go on to say that due to reciprocity failures in high intensity light fading tests, and because of the abnormal higher temperatures that can occur during exposure, predictive tests may not be reliable when based on a single accelerated test condition.

3.5.3 Natural daylight accelerated ageing

Historically, natural daylight has been the preferred source for lighting works of art. Natural daylight tends to be the most damaging form of light to exhibits, since it contains large quantities of UV radiation and is of variable intensity (Norton, 1957, Bullock and Saunders, 1999). In a museum or gallery, the UV radiation is often controlled by placing UV filters over all the windows.

Standard test methods have been introduced for natural daylight ageing by the British Standards Institute (BS 1006, 1990)[38] (see 4.4.5). For tests conducted in the northern hemisphere, south facing exposures are preferred, because north facing daylight contains too much UV radiation, which can lead to reciprocity failure (Wilhelm *et al.*, 1994). Testing is usually performed during the summer months because more UV radiation is present in overcast skies and during the winter months, and the number of hours of sunlight is low. However, tests can run for several years, such as the tests conducted by Wilhelm and Bower (1994) on colour photographs.

Exposure to natural daylight is discontinuous due to day/night cycles. Daylight also varies due to changes in colour temperature, the angle of the sun to the earth, atmospheric conditions, degree of scattering of light and geographical location (Feller, 1964, Thompson, 1967). Daylight exposures, therefore, are not a reproducible or repeatable light ageing method. Thermal degradation can also be accelerated during hot, sunny days.

3.5.4 Fluorescent light fast ageing

Fluorescent light ageing has become the preferred light ageing method for conservation research because it emits a low amount of IR radiation (Saunders *et al.*, 1994, 1996, Norville-Day, 1994, Norville-Day *et al.*,1998). Previous accelerated light ageing methods, such as mercury-tungsten vapour lamps (see 3.5.5), generate temperature levels that are much higher than normal room conditions. This can lead to overheating of the exposed material, producing thermally induced degradation. These degradation reactions contribute to the final outcome, so that the effect of light exposure is difficult to deduce.

Fluorescent lamps have become a major method of lighting, particularly in offices, factories and public places. The efficiency of fluorescent light relative to tungsten lamps has also led to their increasing use in museums and galleries (Saunders, 1989). Fluorescent lamps are examples of line sources. Line sources radiate light at specific wavelengths. Fluorescent lamps tend to have four peaks in the visible region of the spectrum and one peak in the UV region. They have a high UV content, which varies with each lamp type, but is generally in the region 40 – 150 $\mu W\ lumen^{-1}$ (Saunders, 1989).

Fluorescent lamps can be classified according to the different phosphors that coat the glass tube, that are used to distribute the light emitted to other wavelengths of the visible spectrum[39]. The ANSI/NAPM IT9.9-1996, *Stability of Color Photographic Images – Methods for Measuring* and Wilhelm and Bower (1994) recommend 'cool white' fluorescent light for accelerated ageing tests. This is because this type of lamp is the most common form of fluorescent tube employed, and it is very energy efficient.

3.5.5 Mercury-vapour light fast testing lamps

The standard high-pressure mercury-vapour lamp employed for street lighting has been used since 1952 for research into light fading. A later introduction was a lamp that combined a mercury arc and a tungsten filament in the same globe, with an internal phosphor coating, (MBTF) (Giles, Shah and Baillie, 1969). It has higher emission at the red end of the spectrum than the mercury lamp, but the source is still deficient in yellow and red regions of the visible spectrum (Nassau, 1980). The lamp is a line source and has prominent lines in the green and the violet regions of the visible spectrum, and it emits UV radiation up to 310 nm (Giles and Forrester, 1980). The energy distribution of this lamp simulates daylight better than the original mercury lamp. Previous research has shown that when the system is operated at 45 % R.H. the results produced "*agree very well with daylight, xenon arc and places blue wool standards correctly with an interval of 2.1 up to grade 6*"[40].

3.5.6 Tungsten-halogen light accelerated ageing

The tungsten-halogen lamp (also known as the quartz halogen lamp) operates on a similar principle to the tungsten incandescent lamp. A filament of tungsten is heated by an electrical current to a temperature at which it emits light as well as heat. In the presence of halogen gas, the tungsten filament can be heated to higher temperatures with longer lifetimes than ordinary tungsten-filament lamps. When tungsten evaporates from the lamp filament of an ordinary light bulb, it forms a dark deposit on the glass envelope. In the presence of halogen gas, it reacts to form a gaseous tungsten halide, which then migrates back to the hot filament, where it decomposes, depositing some tungsten back to the filament and releasing halogen back into the bulb atmosphere. The process is then repeated (Sinclair, 1997). The source has a higher colour temperature than an incandescent lamp and therefore, produces a 'whiter' light. The lamp emits significant energy in both the long and short wavelengths, including UV and IR radiation[41]. This form of lighting is frequently found in museums, galleries and public buildings to illuminate art works. UV radiation can be removed with filters, and manufacturers, such as Osram and Philips, are now supplying tungsten-halogen spot lamps with the UV filters built in.

3.5.7 Other light accelerated ageing methods

3.5.7.1 Xenon arc lamp

The xenon arc lamp is the most popular light fast testing method employed by industry. The lamp is often considered as a substitute for daylight, since its light approximates to global radiation when filtered, so that the ultraviolet cut-off coincides with that of daylight and the excess of IR radiation is absorbed (Friele, 1963). The machine can operate with day/night cycles, to further simulate natural daylight exposure. Previous research has shown that this cyclical method can produce different fading results compared to continuous exposures (Pretzel, 2000, Gillet *et al.*, 2000). This outcome has been attributed to localised heating effects that can occur with the high levels of radiation emitted depleting water or oxygen levels needed for fading reactions (Pretzel, 2000).

3.5.7.2 Incandescent light accelerated ageing

Tungsten lamps are widely used for lighting in museums and galleries. The lamps are used because they emit radiation with a smooth spectral distribution, although lacking intensity at the violet and blue end, with low UV radiation content[42]. Tungsten lamps emit a lot of IR radiation, which make them unsuitable for high intensive light exposure, due to the inability to maintain moderate experimental temperatures. The ANSI/NAPM IT9.9-1996 discusses the use of an accelerated test method using tungsten illumination at 3 klux intensity. Wilhelm and Bower (1994) also documents light fast testing research using tungsten illumination at 1.35 klux.

3.5.7.3 Carbon-arc light accelerated ageing

One of the original methods for light fast testing, this source has been found to contain large quantities of UV radiation that are not present in natural daylight. Therefore, this test method is not employed for conservation research.

3.5.7.4 Recent innovative light fast testing methods

Recently, two new light fast testing instruments have been introduced that are designed to identify fugitive materials rapidly (more light sensitive than blue wool dyeing No. 2) and essentially non-destructively (Whitemore, 1999, 2000, Pretzel, 2000). The light fast testing technique, termed 'microfading', has been found to compare well with results collected from conventional accelerating ageing tests mentioned above (Whitemore, 2000). Testing involves exposing a very small area (0.4mm) of an object to a high intensity of light, for only a few minutes. During this exposure, the machine measures the fading rate of the area. Exposure is controlled to cause fading up to a ΔE_{ab} value of 5, which is can be just perceivable by the human eye. The method is able to directly identify light sensitive colourants accurately and without damaging the object (Whitemore, 2000).

3.5.8 Thermal ageing

Paper is composed of organic materials, and like all organic materials, it is subjected to a number of deterioration processes over time. These processes can be very slow. To assess the effects of ageing that would naturally occur in long-term dark storage, elevated temperatures are employed to accelerate reactions in the substrate. Heat is used since most chemical reactions proceed faster at higher temperatures. Thermal/dark ageing is employed to assess the effects of deterioration of paper such as yellowing and loss of strength (Porck, 2000, Smith and Gkinni, 2000).

3.5.8.1 Arrhenius testing

A predictive test can be based on the Arrhenius equation (see equation 3.2) formulated in the late 1800's by Swedish physicist and chemist Svante August Arrhenius (1859-1927), to describe the relationship between temperature on the rate of chemical reactions (Wilhelm *et al.*, 1994, Porck, 2000, Smith *et al.*, 2000).

$$k=Ae^{-E/RT} \tag{3.2}$$

Where k is the rate constant, T is the absolute temperature and R is the gas constant. A and e are constants for a particular reason, E is known as the activation energy. To apply this equation, it is necessary to determine the rate of change with time of a suitable property at a number of different temperatures, often at controlled relative humidity (Smith *et al.*, 2000, Porck, 2000). To assess discolouration ΔE_{ab} or density might be used, whilst for physical degradation fold endurance or tensile strength might be applicable. The equation shows that if the rate of change on logarithmic scale is plotted against the reciprocal of the temperature, a straight line should result. In principle, this line can be extrapolated to give an estimate of the rate of degradation at ambient temperatures.

The Arrhenius test is a better indicator of the ageing of paper than just one single accelerated temperature test. The test, however, depends on a long extrapolation which limits accuracy. It also assumes that ageing reactions are the same at elevated and ambient temperatures. Therefore, the test is employed to give an indication of the tendency for a material to undergo chemical reactions (Smith *et al.*, 2000, Porck, 2000). Research is currently being undertaken at the National Gallery, London, to investigate the use of light ageing together with thermal ageing. The test aims to establish that employing both procedures together may give a better indication of the ageing of paper materials on display[43].

3.6 CONSERVATION TREATMENTS

Interventional conservation treatments are employed to stabilise the condition of an object that has suffered physical damage and/or deterioration. A basic range of treatments used in paper conservation has been reviewed for use with the printed materials (see 4.5.4). The following range of conservation treatments were employed for the investigation.

3.6.1 Mechanical dry cleaning

Mechanical dry cleaning is used to remove or reduce the potential for damage to paper artefacts caused by foreign material which can be abrasive, acidic, hygroscopic, or can lead to degradation. Treatment can also be considered for aesthetic reasons when surface dirt interferes with the visibility of the image or information. Surface dirt can be caused by the following:

- Soil, dust
- Soot, grime
- Airborne pollutants and particulates
- Vandalism and accidental damage
- Accretions caused by pests, adhesives, wax, etc.
- Fungi
- Smudged or displace media
- Adhesive or other construction materials
- Fingerprints/footprints
- Remnants of previous conservation treatments

A range of different eraser materials are employed for the treatment, such as polyvinyl chloride based erasers, Factice (vulcanised vegetable oil), latex sponge, pad erasers and brushes. Erasers should be selected that will not damage or physically alter paper surfaces and media. Mechanical dry cleaning methods can be adapted to suit the material, for example grating of the eraser instead of using it in solid form (Sterlini, 1995, AIC, 1992, Banks, 1969).

3.6.2 Aqueous-based treatments

Various aqueous-based treatments are employed in conservation to aid the removal of soluble degradation particulates and discolouration (AIC, 1990, Lienardy and Damme, 1990). Aqueous treatments are also used prior to certain treatments such as deacidifying and bleaching, and can be used to flush residual chemical agents from other conservation treatments, such as stain removal and adhesive chemicals. Aqueous treatments are irreversible but are employed in conservation, as they can be very beneficial to paper often improving the elasticity of the substrate by replenishing the hydrogen bonds between the cellulose molecules. Aqueous treatments, however, can also be detrimental to an object if the media or binder is fugitive, the paper support suffers distortions from uneven wetting of the substrate, the object is not fully supported by the washing material, surface information can be lost from immersion, such as the raised 'burr' on mezzotint prints. Aqueous treatments include humidification (see 4.5.4.2), localised spot washing, felt/blotter washing[44], float washing[45], screen washing[46] and immersion (see 4.5.4.3) for example.

Solvents, such as industrial methylated spirits (IMS) (95 % (v/v) ethanol, 5 % (v/v) methanol) can be employed with the aqueous treatments to improve the wettability of the wash water, or used instead of water for localised washing, if the media present on the paper is soluble in water but not in the solvent (AIC, 1990, Lienardy *et al.*, 1990, Hey, 1979).

De-acidification agents such as calcium hydroxide ($Ca(OH)_2$) and magnesium hydrogen carbonate ($Mg(HCO_3)_2$) solutions can be employed with aqueous treatments to raise the pH level of the paper (Bansa, 1998, Daniels, 1987, 1980, Hey, 1979). Paper can become acidic over time through auto-oxidation processes, which can lead to discolouration and loss of mechanical strength. Introduction of wash treatments increase the pH level of degraded paper, but de-acidifying agents can be used in addition for particularly acidic papers (below pH 4.5). Application of certain de-acidifying agents can also leave a residual alkaline buffer within the paper, which can protect the paper against acid attack. De-acidifying treatments can be detrimental to objects, causing colour change of certain colourants, can darken some papers (for example papers that contain wood pulp), colourant binders can become soluble and white 'blooming' can occur where deposits of calcium carbonate can be left on the surface of the print.

3.6.3 Tear repair

Tear repairs are used in conservation to join splits and tears or reinforce cracks that have occurred in the paper substrate (see 4.5.4.6). A variety of different papers can be selected for the process and can be adhered to the material in various ways (AIC, 1984, Jones, 1978). Tear repairs are a reversible treatment that can restore the aesthetic unity of the sheet and improve its physical strength.

3.7 PREVIOUSLY PUBLISHED LITERATURE

3.7.1 Light fastness and thermal ageing of digital printed materials

3.7.1.1 Wilhelm Imaging Research Inc.

Henry Wilhelm of Wilhelm Imaging Research Inc., is a recognised specialist on the light fastness of digital printing, particularly ink jet technology. He has published many articles and co-authored the book with Carol Bower *The Permanence and Care of Color Photographs: traditional and digital color prints, color negatives, slides and motion pictures* (1994). He is also a founding member of the ANSI subcommittee on the test methods for the evaluation of permanence of colour photographs and digital images.

Wilhelm Imaging Research Inc., established in 1995, is an independent light fastness- and dark/thermal-testing laboratory based in Iowa, U.S.A. The company is employed by the photographic and digital printing industries to test their products before they are released onto the market. The company publishes 'predictive years of display' for a variety of ink jet and photographic material on their website[47]. All of the results published are for one type of fluorescent light exposure (see table 4.2), and the density measurement is used to calculate the fading rates. Light fastness results range from 1-2 years to greater than 150 years. The 'display life predictions' are calculated for indoor conditions of 450 lux for 12 hours per day, at 75 °F and 60 % RH. He does not specify whether UV radiation is filtered out, and the 'display life predictions' are based on an "*easily noticeable fading limit, changes in color balance, and/or staining*" (Wilhelm, 1999). Two sets of fading limits are discussed in *The Permanence and Care of Color Photographs*, by Wilhelm and Bower (1994), for the light testing of colour photographs and digital prints. One set of image fading and staining limits are employed for general use, and allows a substantial degree of fading and change in colour balance to occur before the limits are reached. This limit is set at 30 % change in density. The second set of image fading limits uses a much smaller loss of density, and is intended for museum and archive applications. This is set at 10 % change in density. Wilhelm and Bower tend to refer to the fading limit of 30 % change in density in their book when publishing light fading results. This limit is also recommended by the ANSI/NAPM IT9.9-1996 and Hendricks (1991) to evaluate the fading prediction time of colour photographs. Therefore, the results published by Wilhelm may not follow the standards required for museum and gallery display.

Testing is conducted using a wide variety of uncoated and coated papers. Results show that the type of paper used with ink jet printing can lead to a significant difference in the light fast stability of the final image (see 3.7.4). Wilhelm Imaging Inc. also uses a wide variety of different ink combinations and concentrations, to gain a complete understanding of the light fastness of an ink set (Wilhelm *et al.*, 1994).

3.7.1.2 The Centre of Research for the Conservation of Graphic Documents

The Centre of Research for the Conservation of Graphic Documents, based in Paris, France, has conducted an investigation into the light fastness of Iris ink jet prints and compared the results to two Fuji photographic processes (Gillet *et al.*, 2000)[48]. Iris test samples were produced with nine different uncoated and coated papers, and two coated canvas supports, using the Iris Equipoise ink set. Light fastness testing was conducted using metal halide and fluorescent light sources. Two exposures were made with the metal halide lamp, at 14 klux and 35 klux, and the fluorescent exposure was conducted at 9 klux. This research indicated that the samples exposed to the 35 klux metal halide test exhibited slower fading rates than the same samples exposed to the 14 klux test. This result was attributed to reciprocity failure (also see 3.5.2). This result also indicated that the Iris ink degraded at a faster rate printed on the coated Iris ink jet papers and canvas compared to the uncoated papers tested (Arches vélin and aquarelle). Display life limits of the prints were not published with this research.

3.7.1.3 Rochester Institute of Technology

Based in New York, U.S.A., the Rochester Institute of Technology is another independent light fast and dark/thermal ageing testing laboratory that specialises in photographic work, including digital printing. The institute supports a variety of research projects. One of their researchers, Martin Jürgens, has published two extensive papers on the *Preservation on Ink Jet Hard Copies* (1999) and *Digital print identification website and the process database* (2000). The first paper gives a thorough description of ink jet technology, and the second paper establishes some identifying techniques for the classification for the different types of digital prints.

3.7.1.4 The Tate Gallery

Heather Norville-Day has published two research papers on the light fastness of ink jet and electrophotographic printed materials (Norville-Day, 1994, Norville-Day *et al.*, 1998). The first paper (Norville-Day, 1994) looks at the preservation and conservation of faxes and colour photocopies, with reference to the work by David Hockney, titled 'Home Made Prints'. Photocopied samples were exposed to accelerated light and thermal ageing conditions. The samples were produced following the method used by Hockney that is of putting the same sheet of paper through the copier up to three times, building up layers of toner. After light ageing only some of the toners showed slight fading, but after thermal ageing it was noticed that the toner exhibited pronounced crazing. This outcome was more severe where there were two or more layers of toner.

Six basic conservation treatments were tested on the photocopy samples: washing; low pH; high pH; solvents; bleach; and mechanical dry cleaning. With the washing treatments, the toner was resistant to water penetration. This caused uneven wetting, leading to the distortion of the paper. Continuous emersions led to the paper splitting where the toner was applied in thin layers. The samples were unaffected by the changes in pH, but were found to be fugitive to various solvents. Localised bleaching was found to be effective instead of immersion, because water penetrated the samples unevenly. Toner was removed with the mechanically dry cleaning treatment.

Norville-Day co authored another research paper with Shulla Jacques on the light fastness and dark/thermal ageing of ink jet, litho stochastic[49] and pigment transfer printing[50]. Samples of ink jet printing were obtained from the Hewlett Packard Desk Jet 690C printer. After light ageing, all of the ink jet inks showed pronounced fading except for the black ink. These samples exhibited much higher fading rates compared to the other pigment transfer and litho stochastic processes tested. After thermal ageing, the cyan, magenta and yellow inks from the ink jet samples exhibited significant colour change. Therefore, the authors advised that the material was not recommended for dark storage. Ink jet samples were tested with deionised water and IMS (methanol) spot tests. The tests found that the prints were sensitive to both water and the solvents used in testing.

3.7.1.5 Camberwell College of Arts

An investigation into the dark/thermal ageing of ink jet printed materials has been conducted by Smith and Gkinni (2000). The research involved thermally (80 °C, 50 % RH) ageing a wide variety of ink jet printed samples, and took into account the effect of different ink jet ink combinations and concentrations. After thermal ageing, a pronounced yellowing was found to occur with all of the papers tested. Little obvious fading or colour shifts occurred, but the high temperature used for thermal ageing did appear to cause some migration of the colourant, but explained that further testing would be needed to confirm this. Overall, thermal ageing did not appear to affect the material with regards to the colourant.

3.7.1.6 FOGRA

FOGRA based in München, Germany have published results for the light fastness and mechanical resistance of electrophotographic printings (Schiller, 2000). They tested four different electrophotographic printers: Indigo E-Print 1000; Xerox 5790; Canon CLC 700: Xeikon DCP 32-D. They found that the Indigo prints showed less rub resistance than the Canon, Xerox and Xeikon samples, which generally had good resistance to the test. The print samples were also fugitive to the solvents tested (ethyl alcohol (96 % v/v), and a solvent mixture of ethyl alcohol (60 % v/v), ethyl acetate (30 % v/v), monopropylene glycol methyl ether (10 % v/v)). Sodium hydroxide solution was also tested with the samples and they were all found to be alkali fast. Overall, all of the print samples tested showed good light fastness (see table 3.2), but the paper was found to yellow on exposure to light due to the presence of lignin.

Table 3.2 Light fastness results (blue wool scale ratings) from the FOGRA study (reproduced from Schiller, 2000).

Printer	*Cyan*	*Magenta*	*Yellow*
Indigo E-Print 1000	6	6	4
Xeikon DCP 32-D	6	5 - 6	6
Xerox 5790	6	6	5
Canon CLC 700	6	4	5 - 6

3.7.1.7 Pira International

Research by Chamberlain (2000) from Pira International, Leatherhead, UK, found that after a combination of light and thermal/dark ageing laser printed samples produced on four different types of paper (printer and paper were not specified), the toner remained unchanged, but the paper had discoloured. Rub resistance and toner adhesion tests showed some improvement after thermal ageing at 50 °C, and a further improvement after thermal ageing at 80 °C. Tests for fold endurance were also performed, and the results found that surface cracks can propagate in various ways through the paper causing unsightly appearance and reduction in tensile strength.

3.7.1.8 Other light fast testing investigations of digital print materials

Other light fast testing studies are also regularly published in the popular photographic publications. Hofmann from the testing laboratories at Ilford, Switzerland, have investigated the light fastness of various ink jet printed samples for the BJP (British Journal of Photography (2) 2000). Samples were produced from the Epson Stylus Photo 1200, Epson Stylus 900, and the Epson Stylus Photo FX printers using Epson and Lyson ink sets and various ink jet coated papers. Light testing was conducted using an Atlas Ci-4000 rig and any colour changes were recorded with a densitometer. Their results showed that nearly all of the print samples would exhibit noticeable fading after four years or less on display at 450 lux. Ilford states that their findings were similar to the light fast testing results published by Wilhelm Imaging Inc. for the same print media (see 3.7.1.1).

3.7.2 The effect of humidity on ink jet prints

High relative humidity levels have been found to have serious effect on ink jet prints (Robb, 2000). Humidity levels over 80% RH can cause the ink to migrate and bleed into substrate leading to overall imaging becoming less dense and the colours muted. Recommended exhibition conditions for ink jet prints are 70 °F/ 21 °C and 40 % - 50 % RH. For storage, 65 °F/16 °C and 35 % - 40 % RH is advised.

3.7.3 The effect of atmospheric pollutants on the stability of ink jet prints

Recently, it has been found that ink jet prints can be sensitive to atmospheric ozone (Farr, 2000, Fraser, 2000). Ozone (O_3) is a powerful oxidant to almost all organic materials[51], and is a common air pollutant that occurs naturally in clean air. It is also found at somewhat higher concentrations in urban areas where photochemical smog is generated. Studies have demonstrated that significant amounts of ozone present in the outdoor atmosphere can invade a museum environment (Whitemore, 1987). However, in non-ventilated rooms it has a very short indoor life, because it is easily destroyed by organic materials including presumably by humans and exhibits (Thompson, 1986).

Another investigation has been conducted to establish the cause of yellowing in coated papers (Mailly *et al.*, 1997). The yellowing was due to the action of nitrogen oxide (NO_2) on antioxidants in latexes and fluorescent agents found in coated papers. Ammonia (NH_3) was found to intensify the reaction caused by NO_2 acting on the latexes but not on the fluorescent agents.

The coated papers were also exposed to accelerated light and dark/thermal ageing tests. The latex in the coated papers exhibited yellowing with radiations of 400 nm - 470 nm spectral region (Mailly *et al.*, 1997). Heat and humidity, however, led to a greater degree of yellowing compared to radiation in the yellowing of latex (Mailly *et al.*, 1997).

3.7.4 The effect of paper on the light fastness of ink jet prints

The effect of the paper substrate on the light stability of ink jet printing has been well recognised in the literature (Jürgens, 2000, Wilhelm, 1999, 2000, Gillet *et al.*, 2000, McManus *et al.*, 1983, Lavery *et al.*, 1998, Lavery, 2000). Wilhelm has shown that the light fastness of a dye can differ by a factor of over 100 times depending on the paper substrate it is printed on (Wilhelm, 1999). Iris ink jet inks have been found to have a higher light fastness rating on uncoated papers than on the supplied coated papers (Wilhelm, 1999, 2000, Gillet *at al.*, 2000). The reason given is that the coated papers maintain the ink near the surface of the substrate, which keeps more of the ink in direct contact with light, fading it much more quickly. The uncoated paper also permits more of the ink droplets to mix together allowing for hydrogen bonding between the molecules to take place. The extensive papers perform better than other uncoated papers. After discussions with the paper manufacturers Inveresk, they said that the presence of gelatine in the paper was believed to be responsible for improved light fast characteristics of ink jet inks. Jürgens (1999) also comments that gelatine present in paper can function as a mordant to ink jet inks (see 3.2.5).

Current dye-based ink jet prints are more sensitive to light than colour photographs primarily due to the media on the dyes are places, not the dyes themselves, because ink jet dyes have inherently higher light stability than silver halide dyes (Gregory, 2000). A dye may suffer rapid photochemical degradation on one substrate, only to show superior light fastness on another. Particularly important variables are the physical form of the dye, the moisture content of the substrate, the availability of oxygen within the substrate, and the chemical structure of the substrate itself (Griffiths, 1972). Differences in the depth of dyeing may also produce differences in light fastness of 2 or 3 blue wool scale grades (McLaren, 1956).

3.7.5 Catalytic fading of ink jet inks

When ink jet inks are printed together on a substrate certain dye mixtures can influence each other, causing the mixtures to have different chemical properties than the individual inks alone (Vanmaela, 1995). This may involve the accelerated photo oxidation of the least stable chromophore in the mixture (Lavery *et al.*, 1998).

Russell and Abney (1888) (see Bromelle, 1964) also found that the rate of fading of watercolours faded more quickly in mixtures than separately. Abney quotes in a later lecture, "*when mixtures of colours are employed those colours which are more or less fugitive have a greater tendency to fade than when tested alone*"[52].

3.7.6 The effect of concentration on the light fastness of ink jet prints

The effect of concentration of ink on the surface of a substrate has been acknowledged as a significant factor in the light stability of an image since early investigations into light fast testing (Bromelle, 1964, Padfield and Landi, 1966)[53]. Recent studies into the light stability of continuous tone (contone) ink jet printing (Allred and Schwartz, 1994) have further investigated this phenomenon and have found that the characteristic image forming dots have a higher sensitivity to light when discretely printed than when printed in a solid form. The research concluded that this was due to the internal reflectance of light within the paper and at the edge of the substrate, which affected the dots printed at 5% to 50 % print concentrations. They found that initial ink concentrations of 5 % to 20 % produced a sharp rise in light fastness and then after peaking at 20 % ink concentration, the light sensitivity of the more heavier ink printed regions began to decline. The internal reflectance theory was supported by additional research by Allred and Schwartz (1994), using ink diluted to 20 % of the control ink used previously. After accelerated ageing, the light stability of the lower dye concentration ink (printed at 100 % ink intensity) was significantly better than the previous tested ink (printed at 20 % ink intensity). Overall, the lower concentration dye faded to one third of the rate of the higher concentration dye at similar intensities.

3.7.7 Colour gamut and the light fastness of ink jet prints

It has been recognised that there is an inverse relationship between the colour gamut of an ink jet ink set and its light fastness (Jürgens, 1999). Research has shown that if the ink set has a wide colour gamut, the light fastness of that ink set is relatively low. For a small printable colour range, the light stability tends to high.

[1] www.scitex.com
[2] www.iafadp.com
[3] *"In a blind test people generally choose ink jet prints over silver halide prints because it looks vibrant because ink jet dyes are brighter than silver halide dyes."* Gregory (2000), p. 41.
[4] *"The mechanism by which a liquid stream breaks up into droplets was described by Lord Rayleigh in 1878, and the first practical use of the phenomenon for a recording device was described in 1930. The first successful product using ink jet, again as a recording device, was developed by Rune Elmqvist of Siemens in 1951. In the early 1960s, Richard Sweet if Stanford University developed continuous ink jet technology. In 1967 Carl Hertz, from the Lund Institute in Sweden, modified Sweet's technology to produce 'grey-scales'......and licensed the device to Iris Graphics and Stork who then produced commercial high quality printers for the pre-press industry."* Gregory (2000), p. 39.
[5] Printers of this type have been labelled 'Super wide format', and are used to print posters and banners. Super-wide Format Supplement (2000).
[6] Solvent-based inks are used for faster drying times, and for printing on hydrophobic substrates such as metals, plastics or glass. Kenyon (1996), p. 120.
[7] Typically, ethylene glycol and glycerol (Lyne and Aspler, 1984),, diethylene glycol (Kenyon, 1996), or Polyethylenglycol (Weber, 1991).
[8] For example, chloride ions present in the dye. Kenyon (1996), p. 120.
[9] If too much ink is sprayed onto the paper, the excess of absorbance capacity of the substrate can lead to 'bronzing' of black ink. Jürgens (1999), p. 30.
[10] For example, kaolin (hydrated aluminium silicate), calcium or magnesium carbonate, silica aerogel (an almost pure, very transparent form of silica), or talc (hydrated magnesium silicate) can be used as extenders. Calcium or magnesium carbonate will leave a dull surface to the dried ink, and talc will give a velvety finish. Jürgens (2000), p. 37.
[11] *"Avecia are currently developing dyes that have instantaneous 100 % water fastness whilst maintaining their chroma, light fastness and reliability. This requires a new approach. On the pape,r the dye is water fast because of zwitterions formation between the protonated amino groups and the sulfonate groups. This leads to insolubility and strong H-bonding between the dye and cellulose because of the close stereochemical fit"*. Gregory (2000), p. 41, also see Gregory *et al.* (2000), p. 42.
[12] Electronic and chemical companies such as BASF, Bayer and Hoechst from Germany, Sandoz and Ciba-Geigy from Switzerland and Avecia from the UK, have been involved with the development of new dyes for ink jet. Gregory (2000), p. 40.
[13] *"Dyes are more vibrant due to the fact that their units are single molecules, which are smaller than the particles of pigments, which have surface characteristics that refract light, thus adding a certain amount of noise to the reflected light which in turn leads to a duller of matter surface"*. Jürgens (1999), p. 31.
[14] Anthraquinones – are generally used in solvent based or hot-melt inks. Jürgens (1999), p. 31.
[15] This dye has moderate to low light fastness. Kenyon (1996), p. 122.
[16] Due to thermal stability, this dye is used for bubble jets. Bauer *et al.* (1995), p. 410.
[17] CI Direct Black 171 is used for non-thermal ink jet systems. Bauer *et al.* (1995), p. 410.
[18] Dye used in admixture with other dyes to enhance chroma. Gregory *et al.* (2000), p. 42.
[19] *"Oxidative fading of the azo dye involves the attack of singlet oxygen on the azo or the hydrazo tautomer to produce a peroxide which rapidly decomposes producing the naphthoquinone"*. Lavery *et al.* (1998), p. 124.
[20] The structure of cyclodextrin allows it to hold an equally hydrophobic (and thus waterfast) dye without interfering with the colour of that dye. Cyclodextrin has a great affinity to associate with cellulose, as it is structurally and chemically very similar. Jürgens (1999), p. 36.
[21] *"Chromophores are chains of atoms that have single and double bonds between them and are a part of the structural skeleton of the molecule. Auxochromes are functional groups that can be either organic or salt-forming and are attached to the molecule to modify and/or intensify the colour of that substance. The complete molecule without the auxochrome is usually termed a chromogen"*. Jürgens (1999), p. 34.
[22] Artists from the Integration of Computers into Fine Art Printmaking project, based at

Camberwell College of Arts, London (see 2.1), have used both traditional and uncoated papers for ink jet printing. They have found that the ink jet coated papers tend to be difficult to frame because they are relatively thin (below 200 gsm) and do not lie flat in the frame.

[23] Such as naphthol-based disazo pigments, a new yellow colourant based on 5-aminobenzimidazolone, magenta toners involve azothiazoles, azobenzothiazoles, and anthraquinones. Zeneca developed the fluorosulphonylphenylazoanilines for ink and toner compositions comprising solids having low melting points. Freeman and Sokolowska (1999), p. 14-15.

[24] Colourless CCAs suitable for use with coloured pigments include Cr^{3+} and Co^{3+} complexes with salicylate compounds. Thompson (1998), p. 459.

[25] "*The radiation wavelengths of interest are in the 700 - 200 nm range. Most light sources do not subject objects to radiation of wavelengths less than 270 nm. Photochemistry fading in practical situations comes about because of radiation in the 300 - 700 nm region*". Brill (1980), p. 178.

[26] Thermal equilibrium, internal conversion, radiationless deactivation, intersystem crossing, fluorescence, phosphorescence, chemical reaction, sensitisation or emission quenching. Owen (1980), p. 8-12.

[27] "*The photochemical process leading to dye destruction is said to have a 'quantum yield' of about 10^{-6} or less*". Sinclair (1997), p. 53.

[28] The light activated dye is usually oxidised by a hydroperoxide radical (HO_2), which is itself formed by the light-induced reaction between oxygen and water. The HO_2 is a very reactive, strong oxidising agent. Brill (1980), p. 182

[29] A mechanism whereby an energy-activated dye reacts with a neighbouring molecule, such as the fibre to which it is bound, to reduce the dye and oxidize the fibre. Brill (1980), p. 180.

[30] A decomposition pathway characteristic of very light fast dyes. Very light fast dyes tend not to be significantly sensitive to light of wavelengths longer than 400 nm, but the fibre rather than the dye absorbs light and causes reduction of the dye bound to the fibre, or the in some cases the dye may act to transfer absorbed energy to the fibre. Both the fibre and the dye are decomposed as the result. Brill (1980), p. 183.

[31] The sensitivity of a colourant system to different wavelengths of light is known as its 'action spectrum'. Feller (1994), p. 63.

[32] The spectrum was roughly divided into three sections by using red, blue, green filter glass, which transmitted the two ends and the central regions respectively of the spectrum. Brommelle (1964) after Russell, Abney (1888), p. 147.

[33] A plot of the logarithm of this damage factor, $D(\lambda)$, against wavelength has a slope of around $-1/90\ nm^{-1}$. Saunders *et al.* (1994), p. 190.

[34] P. 108

[35] www.wilhelm-imaging.org.

[36] Wilhelm *et al.* (1994) suggests light exposures of 13.5 klux and below to follow the reciprocity principle, and Gillet *et al.* (2000) found that 9 klux was a suitable exposure.

[37] P. 67

[38] The American National Standards Institute (ANSI) have also published standards for the light ageing of photographic materials using natural daylight. ANSI/NAPM. 1996. Stability of Color Photographic Images – Methods for Measuring (IT9.9-1996).

[39] E.g standard, deluxe, warm, cool.

[40] Giles *et al.* (1969), p. 416. Also see Park and Smith (1974), p. 431-432.

[41] "*At 2800K, which is a typical temperature for a tungsten lamp, the UV content of the light is 67 W lumen^{-1}. Raising the operating temperature to 3400K, characteristic of short –life tungsten halogen lamps, increases the UV content to 165 W lumen^{-1}*". Saunders (1989), p. 61.

[42] Tungsten incandescent lamps have an UV content in the region of 65-75 W lumen^{-1}, depending on the operating temperature of the filament. Saunders (1989), p. 61.

[43] "*...this could be because the light exposure has oxidised the linen, increasing its susceptibility to acid hydrolysis*". Hackney and Hedley (1993), p. 73.

[44] The object to be treated is laid onto either a damp sheet of felt or blotting paper. The damp support allows moisture to slowly seep into the object, and degradation particles and discolouration is removed through capillary action of the washing support.

[45] Float washing is employed when a paper object requires washing, but the media will not tolerate

immersion. The object is support in a water bath by a washing support (for example, Melinex) and water can come into contact with the object without 'crushing' the surface.

[46] Screen washing is similar to float washing, but two screens of the same size are employed, one laid on top of the other. Both screens are placed into a water bath face-to-face, so that their webs are touching. The water level is then brought up to the height of the bottom of the top screen, and the object is laid on top of the upper screen. When the screens are pulled apart suction is created between the two screens, which aid in the removal of degradations products and discolouration.

[47] www.wilhelm-imaging.org.

[48] Samples were produced using the Iris Equipoise ink set on Arches 'aquarelle' and 'vélin' papers, Commercial Iris, Satin finish Iris, BFK Moulin du Gué, Watercolour, Arches for Iris, Iris Canvas and Ilford Canvas. Photography samples tested were Fuji Pictrography and Fujicolor Crystal Archive.

[49] "*Stochastic screening is one of two kinds of frequency-modulated screening techniques, the other being diffusion dither. A four colour stochastic separation is made for printing. The printing process is similar to the pigment transfer prints*". Norville-Day *et al.* (1998), p. 79.

[50] "*The base is coated with a hardened layer of gelatine which, when moistened with water enables the subsequent pigmented gelatine layers to adhere. To prepare a pigment transfer print, the image is digitally colour separated and transferred to a negative. The negatives are used to expose the gelatine tissue to UV light, which hardens the gelatine in the exposed areas. The gelatine is moistened and registered on the base.The unexposed areas are removed with water. Pigments rather than dyes are used in the gelatine tissue*". Norville-Day *et al.* (1998), p. 78-79.

[51] Analogies have been drawn with the mechanism of photochemical action on dyes. Whitemore (1988, 1987).

[52] P. 147.

[53] Both Russell and Abney (1888) (see Bromelle, 1964) and Padfield and Landi (1966) commented that dyes show a greater resistance to fading when heavily applied to cloth or paper than when applied to give pale tints.

4.0 EXPERIMENTAL METHODOLOGY

4.1 INTRODUCTION

The following account of the experimental research conducted for this investigation has been broken down into four sections.

Part 1. Sample Preparation – Explains how the samples were developed for the research, the constraints of the preparation process, and lists the products tested.

Part 2. Accelerated Light Testing – Discusses why different light ageing methods were used, the role of UV and broad-band interference filters, colour measurement devices employed and the formulas used for data analysis.

Part 3. Light Ageing Methods - Reviews the test methods employed for the investigation into the light stability of ink jet and electrophotographic printed materials.

Part 4. Conservation and Analysis Testing - This section describes the method of assessment of various conservation treatments on the print materials, discolouration of coated papers by thermal ageing, identification techniques and analysis of the ink/toner and substrate.

4.2 Part 1. SAMPLE PREPARATION

4.2.1 Products tested

A series of samples of the various print materials were prepared for this research. There are a number of different manufacturers who produce ink jet and electrophotographic printers on the market, a selection of which are repeatedly employed by artists and photographers to reproduce their designs. A survey of the types of printers used for creative artwork was conducted by speaking to artists working with the technology at Camberwell College of Arts (see 2.1) and in independent practice, conversing with art galleries collecting such work[1], and reviewing literature published by journals and on the internet (Artbyte, 1998, Image Reports, 2000, Miller, 1998, Norville-Day, 1994, Norville-Day *et al.*, 1998, Simpson, 1998, Wilhelm *et al.*, 1994, Wilhelm, 1999). Since the market for digital printers is constantly changing with the introduction of new and improved printers, inks and papers[2], this survey was continually updated throughout the duration of the project. Appendix B (pp. B – 338 to B - 340) lists the findings of the survey.

After identifying the principal companies used by artists and photographers, the manufacturers were contacted directly to obtain samples of print material for testing. Unfortunately, not all the manufacturers approached wanted to contribute to the research. The following lists the companies who kindly donated samples for this project.

- Seiko Epson Corporation
- Canon Ltd.
- Lyson Ltd.

Seiko Epson Corporation is the key manufacturer of drop-on-demand ink jet technology. They were particularly generous to the research project by lending one of their large format ink jet printers, the Pro 9000, for the duration of the project.

Both Canon and Lyson produced samples for this research project at their printing studios based in London and Manchester respectively. Canon is one of world's largest manufacture of photocopiers and laser printers for the office environment. Lyson are a very important independent ink manufacture for the printing industry. They make subsidiary refill inks for many of the ink jet printers on the market[3]. Two years ago they also started to produce their own brand of coated ink jet papers for the fine art and photography market called *Soft Fine Art Watercolour Paper* and *Rough Fine Art Watercolour Paper*. Lyson have a contract to supply the *Lysonic* ink set for the Iris ink jet printers[4].

Further samples were obtained from the London based print bureau 'Visualeyes' who kindly supported the project in its first year and donated samples of printing from the Iris 3047 large format ink jet printing using the Morgan FA ink set. Prints were also attained from the Hewlett Packard 3500 DesignJet printer stationed at Camberwell College of Arts. The samples selected for the research are listed in table 4.1. Each sample was given a reference number for the investigation.

Table 4.1 List of printers, paper and ink types investigated.

Printer Type and Model No.	*Substrate Type (Manufacturer)*	*Ink Type (Manufacturer)*	*Assigned Sample No.*
Iris 3047	Somerset Velvet, Radiant White, 280 gsm (Inveresk)	Morgan FA (Owen Morgan)	1.1
Iris 3047	Watercolour, 250 gsm (Whatman)	Morgan FA (Owen Morgan)	1.2
Mutoh Falcon RJ-4000 (Epson Print Engine)[3]	Soft Fine Art Watercolour, 285 gsm (Lyson)	Lysonic (Lyson)	2.1
Mutoh Falcon RJ-4000	Rough Fine Art Watercolour, 210 gsm (Lyson)	Fotonic (Lyson)	2.2
Mutoh Falcon RJ-4000	Watercolour, 250 gsm (Whatman)	Lysonic (Lyson)	2.3
Mutoh Falcon RJ-4000	Watercolour, 250 gsm (Whatman)	Fotonic (Lyson)	2.4
Epson Pro 9000	Photo Glossy, 190 gsm (Epson)	Pro 9000 (Epson)	3.1
Epson Pro 9000	Somerset Velvet Enhanced (ISVE), 225 gsm (Inveresk)	Pro 9000 (Epson)	3.2
Epson Pro 9000	Somerset Velvet, Radiant White, 280 gsm (Inveresk)	Pro 9000 (Epson)	3.3
Epson Pro 9000	Watercolour, 250 gsm (Whatman)	Pro 9000 (Epson)	3.4
Epson Pro 9000	Presentation Matt, 172 gsm (Epson)	Pro 9000 (Epson)	3.5
Epson, Photo Stylus 870	Photo Glossy, 141 gsm (Epson)	Photo Stylus 870 (Epson)	3.6
Hewlett Packard 3500 DesignJet	Heavy Weight Coated Paper – Matt, 130 gsm (Hewlett Packard)	3500 DesignJet (Hewlett Packard)	4.1
Canon 1150 Colour Laser	Ultra White, 105 gsm (Canon)	Toner (Canon)	5.1
Canon 1150 Colour Laser	Card, 209 gsm (Canon)	Toner (Canon)	5.2
Canon CLC 900	Ultra White, 105 gsm (Canon)	Toner (Canon)	5.3
Canon CLBP 460PS	Ultra White, 105 gsm (Canon)	Toner (Canon)	5.4
Canon CLBP 460PS	Card, 209 gsm (Canon)	Toner (Canon)	5.5

4.2.2 Sample design

In the first year of the project, a standard design was devised for the samples. Four different formats were produced to test for the following qualities (see Appendix C (pp. C – 341 to C - 351) for the sample designs),

A. Image quality – to examine quality of colour and line reproduction, reproduction of flesh tone, subtleness of tonal graduation (Eckstein, 1991).

B. Light testing – a series of oblong patches of a selection of particular colours (see 4.2.3) were produced for assessment using different light fast testing apparatus. The patches were made as large as the light testing equipment would allow, so that measurements could easily be taken with the colour measuring equipment and visual comparisons could be made more accurately[6]. The colour patches measured either 20 mm x 20 mm for the fluorescent light testing (see 4.3.3) or 20 mm x 40 mm for all the other tests employed.

C. Conservation testing – a series of oblong patches, the same size as the patches for light testing, were printed using the four basic ink colours CMYK for each conservation treatment to be tested.

D. Control - a series of oblong patches, the same size as the patches used for light and conservation testing, of all the selection of colours used for the light and conservation tests, were drawn to keep for visual comparisons.

The image quality and control also contained a documentation area to record information about the type of print, paper and ink, resolution, ink and paper batch numbers, print operator, and date of issue.

The formats were drawn up using Adobe Illustrator Version 6 and Adobe Photoshop Version 5 programmes for the Apple Mac computer. The images were stored as a computer file that was then copied onto disks and taken to the manufacturers mentioned in 4.2.1 for printing.

Due to the size of the population studied, it became impractical to take an average selection of each of the materials. Therefore, only one sample of each print patch was tested with each investigation, as obtaining an average reading of each printed patch was considered less important than studying the effect of different printers and papers. However, it is acknowledged that an average reading would have recorded a better result.

4.2.3 Selection of colours for testing

The concentration and percentage of all the colours printed was controlled using the Illustrator software mentioned in 4.2.2. The software contains a colour palette that allows the user to specify the percentage of colour required for printing. First, four patches of the basic printing ink colours CMYK were selected at 100 %, 75 %, 50 % and 25 % concentrations, to test the rate of fading of the inks at different printed intensities (see 3.7.6). Then, three patches of the secondary colours of CMY, which are red, green and blue (RGB), were chosen using 100 % concentrations of each of the primary inks. The light fastness rating of the mixture of dyed based CMYK inks can have a faster fading rate than the inks printed on their own. The phenomenon has been termed the 'catalytic fading of dye mixtures'[7] (also see 3.7.5).

The project began without the use of a spectrophotometer to analyse the results. It was therefore decided to include six patches of colour using combinations of CMY at 100 % and 50 % concentrations to help to identify, if it occurred, which ink showed the most fading in a particular combination of colourants. In addition, four more patches of colour were selected using 25 % and 50 % concentrations of CMY printed together and CMYK printed together, to investigate if these ink mixtures had any effect on the light fastness rate. Combinations of 100 % CMY printed with 50 % K were also selected. Each printed patch was labelled with the concentration and combination of ink used.

4.2.4 Production of samples

An effort was made to maintain uniformity in the print production by using the default setting on the colour management software supplied with the printer, although it was observed that each manufacturer used different colour management software[8].

4.2.5 Media selected

Samples were printed on a variety of substrates supplied by the various companies. Research has shown that the substrate can have an important role in determining the light stability and wet fastness of the ink jet ink (Jurgens, 2000, Wilhelm, 1999, 2000, Gillet *et al.* 2000, McManus *et al.*, 1983, Lavery *et al.*, 1998, Lavery, 2000) with manufacturers often matching printing ink to paper (see 3.7.4).

A control paper was selected for printing with each ink set. An uncoated Whatman watercolour paper was chosen for this purpose. The paper was selected because it is a good quality drawing paper made from 100 % cotton, it has a weight of 250 gsm which is suitable for production of fine art prints[9], and because artists often prefer to print on traditional drawing and printmaking papers rather than the digital printing papers[10]. However, due to the mechanical constraints of some of the printers, samples could not obtained from all the Canon laser printers and the Hewlett Packard 3500 DesignJet ink jet printer using the Whatman paper[11].

4.2.6 Conditioning of samples

Before testing commenced, all samples were left in dark storage for a minimum of four weeks, to allow the ink to completely dry and settle on the substrate[12]. Samples were then suspended on a line in a conditioned booth maintained at 21 °C (+/- 2 °C) and 60 % RH (+/- 5 %) for a minimum of one week[13], before any colour measurements were made.

4.2.7 Dark storage of controls

Printing samples were collected throughout the duration of the research project. All samples used for testing were kept flat in manila folders and were stored in the dark.

4.3 Part 2. ACCELERATED LIGHT TESTING

4.3.1 Different light testing methods

Four different light fast testing methods were employed for this investigation. These different test methods were used due to the fact that research into light fastness testing can often be the subject of controversy owing to the many variables involved, with the spectral distribution of the light source being a key factor. As stated by Levison, Sutil and Vanderbrink (1987),

> "*Any one exposure method may give misleading results because of a particular pigment's sensitivity to some aspect of the accelerated test, such as humidity or extreme heat, which would not be encountered in the normal use of the paper.*"[14]

There are seven principal light ageing methods used for commercial testing, they are natural daylight, xenon arc, carbon arc lamps, fluorescent tubes, mercury vapour lamps, tungsten filament lamps and tungsten filament-mercury vapour lamps (Giles *et al.*, 1980). Some light sources, such as the carbon arc lamp, are generally not employed any more as their results do not correlate well with natural ageing conditions[15]. Initially, this project followed the recommended guidelines published in the standards BS 1006 (1990) for the light ageing of textiles and BS ISO 12040 (1997) for the light ageing of print, using the Microscal light fast tester and natural daylight. Later developments in the project lead to further questioning of these test methods and new light ageing apparatus was introduced using fluorescent and halogen light sources.

The main concern of this project was to investigate how light affected the print material. Due to the different nature of the test methods mentioned above, other environmental factors involved with the test conditions, such as humidity, temperature, spectral distribution, etc., were used at varying levels with the different light ageing processes. Therefore, the results from each test method were not directly comparable. However, with each test method, systematic measurements were taken to try and identify the rate of fading of each sample, and the results were compared to see if there were any trends in the fading rates.

4.3.2 UV filters

It has become standard practice to use UV filters in museums and art galleries to filter out the unnecessary and damaging UV portion of the electro-magnetic spectrum. The MNRLW 250 C90 SR Museum Film, manufactured by Film Technologies International Inc., was selected for the investigation, and the film's ability to filter out UV light was tested using a Crawford UV Monitor, Type 760. The film filters out UV radiation in accordance with ASTM E424-71, method A and combined with glass, the film reduces UV radiation by 99 %. Since the ability of protective glasses and foils to absorb UV radiation usually decreases over time the filter was also measured and checked with the UV monitor during long term testing, and new filters were used with each test. The filters were used with the natural daylight, halogen and the fluorescent light sources. An investigation into the effect of UV radiation on the samples was also studied using natural daylight tests.

It was decided not to use UV filters with the Microscal Light Fastness Tester, because of the methodology employed in previous research. Literature published by Giles *et al.* (1969), Park and Davis (1972), Park and Smith (1974) and British standards BS 1006 (1990) and BS ISO 12040 (1997) describe a method of testing where only glass is used to filter out some of the shorter wavelengths of UV radiation (less than 310 nm[16]). The Microscal system is employed to simulate the effects of daylight, but at a much higher intensity, so that the fading rate is accelerated. Since UV filters alter the spectral distribution of the light source, which in turn affects the efficiency of the lamp, it was concluded that using UV filters could alter the relationship of the source with natural daylight conditions.

4.3.3 Broad-band interference filters

The main objective of the light testing investigation was to measure the fading rates of the print materials and study whether variations in the spectral distribution of the light source has a significant effect on the rate of damage. To identify which wavelengths are initiating most of the photochemical reactions, a series of five Dichrolight™ broad band interference filters, manufactured by Unaxis Balzers Limited, were employed to expose the print samples to a selective band of wavelengths (see fig 4.1 for transmission curves of the filters). The filters are constructed from heat resistant borosilicate glass that is coated with a hard and dense dichroic layer. The filter dimensions are 160 mm x 110 mm x 1.1 mm. These filters were used with the fluorescent light fastness test (see 4.4.7)

The Dichrolight™ filters were selected because they were manufactured to a size that allowed the selection of print colours (mentioned in 4.2.3) to be tested together on the same print sample. Dichroic filters transmit virtually no UV light and do not significantly change the colour properties of the light, but additional UV filters (see 4.3.2) were employed with the dichroic filters during light fastness testing, so that all UV radiation was removed. These filters consist of a glass substrate on to which an inorganic coating has been deposited under vacuum. This thin but resilient layer is generally a mixture of metal oxides. Interference effects at the coating interface cause light of particular wavelengths to be reflected whilst light at other wavelengths is transmitted. They were also reasonably priced (£ 22 each direct from the manufacturer) so that several filters of each type could be obtained, allowing for all the samples selected for this experiment to be exposed in the same test. Modifications were made to the light fast testing print design to accommodate for dimensions of the broad-band interference filters (see 4.2.2 B).

Fig. 4.1 Spectral transmission curves for Dichrolight™ filters.

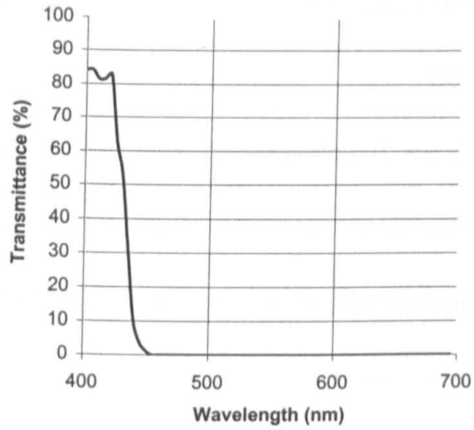

Fig. 4.1.1 Violet dichroic filter.

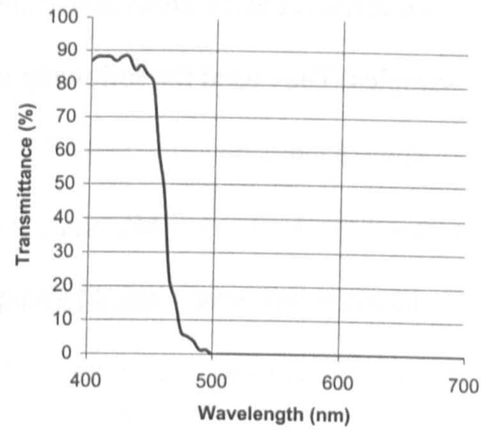

Fig. 4.1.2 Blue dichroic filter.

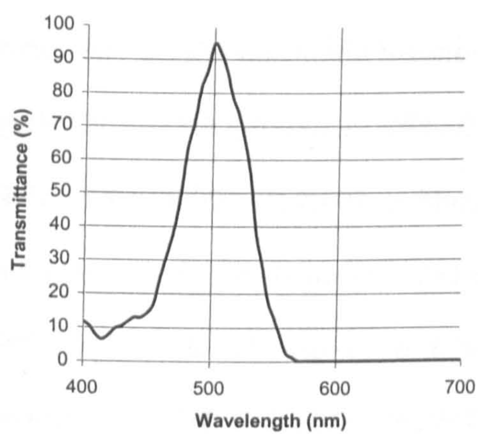

Fig. 4.1.3 Turquoise (Green) dichroic filter.

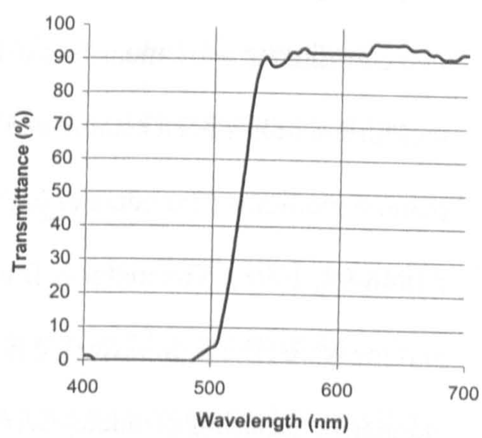

Fig. 4.1.4 Yellow dichroic filter

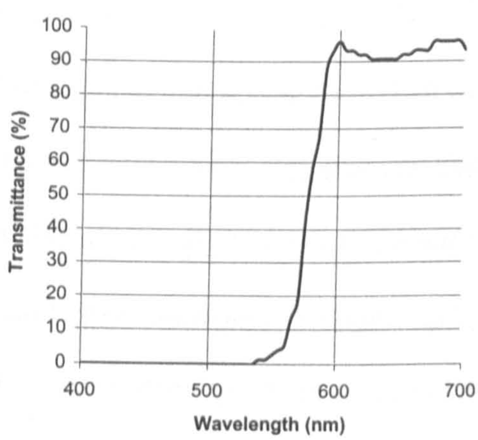

Fig. 4.1.5 Orange dichroic filter.

4.3.4 Colour measurement

Two different methods of colour measurement were used for the assessment of the samples. They used the following instruments:

- Minolta CR300 Chroma Meter
- Xrite Digital Swatchbook Spectrophotometer

The Minolta CR300 Chroma meter was used to record the Commission International de l'Eclairage (CIE) (1978) L^*, a^* and b^* (CIELAB) coordinates adopted by the CIE and Committee of the Society of Dyers and Colourists (SDC). The coordinates were measured using the standard illuminant of D_{65}. This form of measurement has been established as a method for monitoring the rate of fading of painted mediums (Saunders *et al.*, 1994, Schilling, 1993, BS 12040, 1997, ASTM F1946-98, 1998). The meter is fitted with a head to provide diffuse illumination, and measures the light reflected perpendicular to the surface of the sample (this standard measuring geometry is referred to as d/0 and is suitable for measuring matt samples such as printing). The sample head has a diameter of 8mm.

The meter was used to measure the colour of the print samples before and after testing and at set periods during exposure in order to monitor the rate of fading. The measurement of the rate of fading is important because it gives an insight into the whole course of change rather than relying simply on a measurement of the net change over a fixed time (Feller, 1964). Any changes in colour were calculated using the standard ΔE_{ab} equation to record colour difference (BS 6923, 1988) (see

4.3.6). Arrangements were made at the beginning of the project for Minolta to test and calibrate the instrument annually, as recommended by the manufacturer.

Before the measurements began, the meter was calibrated with a standard white tile supplied with the machine. If a large number of samples were measured in one session, the meter would be re-calibrated after every 50 to 55 measurements, to overcome any slight discrepancies that may occur with the device over a period of time[17]. The meter was set to record an average of three measurements for each colour patch, and the standard deviation of the primary CMYK inks from two of the print sample sets, one on coated paper the other on uncoated paper, were measured regularly to monitor the calibration of the machine. Measurements of all the samples were made before light ageing and checks were made to see if the measurements of colour patches remained consistent.

The Xrite Digital Swatchbook spectrophotometer was used to measure the reflectance spectra of all the samples before and after light ageing, to assess the light absorption of the ink patches and to examine whether the absorption curves changed with exposure. Digital Swatchbook is a 16-band colour measurement instrument that reports spectral data to a computer. The standard illuminant of D_{65} was used with all the readings. The machine was regularly calibrated using a standard white tile supplied with the machine. The Swatchbook measures a spectral range from 390 nm to 700 nm and plots the spectral data every 10 nm (32 points). The spectrophotometer uses a measuring geometry of d/0, and the sample head has a diameter of 6 mm.

4.3.5 Average and standard deviation calculations of the results

Both the Chroma meter and spectrophotometer has settings that enabled readings to be taken that are made up of an average of three measurements for all the results. Ten CIELAB measurements were also taken of all the samples exposed to natural light before testing, and two measurements were taken of the CMYK patches for the initial four sets of samples exposed to the Microscal Light Tester. The mean and the standard deviation (SD) of the natural results were calculated. SD was calculated using the following formula:

$$SD = \left[\sum \frac{\left(x - \bar{x}\right)^2}{(n-1)} \right]^{1/2} \tag{4.1}$$

Where x is a reading, $\bar{x}$ is the mean of the readings and n is the number of readings taken. Analysis of the results (see Appendix D (pp. D - 353)) concluded that the printing process facilitated a uniform distribution of ink that led to a very small variation for both calculations. Therefore, due to the number of samples investigated and the time required to measure each patch more than once, further readings were only undertaken to monitor the calibration of the Chroma Meter at various times during the research (ten readings were taken of CMYK patches on a coated gloss and uncoated paper, and the average and SD were calculated). Further readings were also taken to assess the colour of a patch where uneven fading of the ink occurred (five readings were taken, and the average was calculated).

4.3.6 CIELAB colour difference calculation

The colour difference of the CIELAB coordinates was calculated using the standard ΔE_{ab} equation (BS 6923, 1988).

$$\Delta E_{ab} = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{½} \qquad (4.2)$$

Where $\Delta L^* = L^1 - L$; $\Delta a^* = a^1 - a$; $\Delta b^* = b^1 - b$

In recent years there has been some criticism of this equation when applied to colour tolerance evaluation of textiles, paints and printing inks in industry. Results have concluded that calculations using ΔE_{ab} do not necessarily relate to the colour change perceived by the human eye.

> "*Comparisons between the majority visual decision and a numerical assessment, based on the condition that ΔE^*_{ab} must be less that unity for a match, show that the instrument decision will disagree with the majority visual decision about 19% of the time. Pass/fail decisions based on the CIE L*a*b* (1976) equation with a limit of $\Delta E^*_{ab} = 1$ are, on average, slightly less reliable than visual judgements made by a single colourist.*" [18]

Other equations have since been recommended such as the CMC ($l : c$) which has been adopted by the British Standards Institution (BS 6923, 1998) for calculating small colour-difference assessment of textile materials, and CIE94 or ΔE^*_{94} to replace ΔE_{ab} (Heggie, Wardman and Luo, 1996, Li, Yuen, Yeung and Sin, 1999).

$$\Delta E_{CMC(l:c)} = \left[\left(\frac{\Delta L^*}{lS_L}\right)^2 + \left(\frac{\Delta C^*_{ab}}{cS_C}\right)^2 + \left(\frac{\Delta H^*_{ab}}{S_H}\right)^2\right]^{1/2} \qquad (4.3)$$

Where ΔL^*, ΔC^*_{ab} and ΔH^*_{ab} are respectively the CIELAB lightness, chroma and hue differences between batch and standard, l and c are tolerances applied respectively to differences in lightness and chroma relative to that to hue differences (the numerical values used in a given situation being substituted for the characters l and c, for example CMC (2 : 1), whenever there be possible ambiguity, and,

$$S_L = \frac{0.040975L^*_S}{1+0.01765L^*_S} \qquad \text{if} \qquad L^*_S\ 16$$

but $$S_L = 0.511 \qquad \text{if} \qquad L^*_S<16$$

$$S_C = 0.638 + \frac{0.638C^*_{ab,S}}{1+0.0131C^*_{ab,S}}$$

and $$S_H = S_C(TF+1-F)$$

where $$F = \left[\frac{(C^*_{ab,S})^4}{(C^*_{ab,S})^4+1900}\right]^{1/2}$$

and $$T = k_1 + \lfloor k_2 \cos(h_{ab,S}+k_3)\rfloor$$

where $k_1 = 0.36$, $k_2 = 0.4$ and $k_3 = 35$ if H_S 164 or H_S 345

but $k_1 = 0.56$, $k_2 = 0.2$ and $k_3 = 168$ if $164 < H_S < 345$

and L^*_S, $C^*_{ab,S}$ and $h_{ab,S}$ are respectively the the CIELAB lightness, chroma and hue angle (degrees) of the standard (Smith, 1997).

$$\Delta E^*_{94} = \left[\left(\frac{\Delta L^*}{k_L S_L} \right)^2 + \left(\frac{\Delta E^*}{k_C S_C} \right)^2 + \left(\frac{\Delta H^*}{k_H S_H} \right)^2 \right]^{1/2} \qquad (4.4)$$

Where $k_L = 1$, $k_C = 1$, $k_H = 1$, $S_L = 1$, $S_C = 1 + 0.045C^*_{ab,X}$, $S_H = 1 + 0.015C^*_{ab,X}$. The variables k_L, k_C and k_H, akin to the l, c and h of the CMC (l:c) formula, and are referred to as parametric factors. When calculating the colour difference of textiles, better correlation to visual perception of colour difference is achieved when $k_L = 2$ and $k_C = k_H = 1$. S_L, S_C and S_H (ellipsoid semi-axes) are the weighting functions, allowing adjustment of their respective components according to the location of the standard in the CIELAB colour space. $C^*_{ab,X} = C^*_{ab,S}$ the standard of a pair of specimens may be clearly distinguished from the batch. The irreguality of the optimised formulae usually causes the colour difference between a pair of specimens (A and B), when calculated with A as standard, to be different to when B is taken as the standard. The difference is anomalous when neither specimen can logically be designated as the standard, and $C^*_{ab,X}$ may then be defined as the geometric mean of the CIELAB chromas of the pair: $C^*_{ab,X} = (C^*_{ab,A}\, C^*_{ab,B})^{1/2}$ (Smith, 1997).

Both equations have shown to be considerably more reliable than the ΔE_{ab} equation for calculating small colour differences.

> *"Comparison with decisions made by panels of observers show that the equations disagree with the majority decision about 13% of the time."*[19]

However, the ΔE^*_{94} equation has not been approved as a CIE standard because it is only an approximate uniform colour space which can only be used to calculate small to moderate colour differences (less than $\Delta E_{ab} = 5$) (Smith, 1997). The Society for Dyers and Colourists are currently working on a new CIE colour difference formula, CIEDE2000, "*showing much improved performance compared to the existing CIE94 and CMC formulae*"[20]. Therefore, the original ΔE_{ab} equation has been employed to calculate the colour difference of the light fast testing results.

4.3.7 ΔE_{ab} fading limits

Research into colour measurement acknowledges that a ΔE_{ab} of 1.0 is the limit before fading/colour difference is just perceptible by 50 % of viewers (corresponding to the grey scale 4'5) (Gilchrist and Nobbs, 1999). To establish the light fastness of a colourant a just noticeable fade (JNF) limit is employed for the calculations and is usually taken as ΔE_{ab} of 2.0 units (equivalent to the grey scale 4) (Pretzel, 2000).

Light fastness research on the fading of colour photographs often uses the density measurement (see 4.3.9). The acceptable limit of fading is 30 % density loss if the sample is not compared to a reference (Wilhelm *et al.*, 1994, Hendricks *et al.*, 1991). Hendricks also discusses that a 10 % density loss is not perceptible by the human eye unless compared to a reference. All of the results published by Wilhelm Imaging Research use the 30 % density loss as the basis for the 'image life limits' for the fading rates of ink jet and photographic prints.

4.3.8 The blue wool scale

The blue wool scale, recommended by BS 1006 (1990) for assessment of colourfastness[21], is designed as a dosimeter to UV and visible radiation (Bullock *et al.*, 1999). The scale is intended for daylight exposures and supposedly does not fade at the same relative rate in artificial light (Jaeckel, Ward and Hutchings, 1963, Padfield *et al.*, 1966), except for some light testing apparatus such as the Xenon Arc and Microscal lamps which are designed to reproduce natural light, and a similar fading rate is achieved (Giles *et al.*, 1969, Park and Davis, 1972, Park and Smith, 1974). However, other research has shown that the spacing of the standards 1 – 6 is similar in daylight and under warm white fluorescent light, if the standards are regarded as an approximation[22]. It was therefore decided to use the blue wool scale with the fluorescent and halogen lamp tests as a standard reference to monitor the fading rate of different positions under the illuminated area, and to see if there was any correlation in the fading scale under these light sources. A series of blue wool scales were also used to monitor the fading efficiency of the Microscal lamp around its circumference.

The BS 1006 (1990) method of monitoring the rate of fading[23] was not followed for this research since the system of measurement proposed is considered to be subjective and could not be performed with more than one standard viewer[24]. The standard's method for establishing an appropriate exposure time was acknowledged, and applied to the Microscal Light tests, by exposing the samples until one of the primary colour patches reached the degree of fading of between $\Delta E_{ab} = 2.95 - 4.09$, which is equivalent to the grey scale contrast of 3[25].

Only the first seven out of the eight blue wool standards were used for testing because research has shown that the fading rate of blue wool dyeing number eight does not correlate well with the other standards[26]. Colour shifts in the blue wool standards were assessed with the Minolta CR300 Chroma meter and by comparison to the SDC Grey Scale (BS 1006, section A02, 1990)[27]. The degree of fading of the print samples from the natural daylight and Microscal light tests were also compared to the grey scale after light ageing and a blue wool scale rating was given. All visual comparisons were made under the standard D_{50} illuminant for the colour assessment of print in the graphic arts industry (BS 950, Part 2, 1967)[28] against a neutral grey background.

4.3.9 Densitometry

Densitometers are widely used in the graphic art and photographic industries for measuring and controlling each stage of reproduction. The use of a densitometer was considered at the beginning of the research, but was not employed because the density measurement is not as accurate as CIELAB and that it cannot measure colour in relation to the human observer (Popson *et al.*, 1996). A recently published standard, the ASTM F1946 – 98 *Standard Practice for Determining the Lightfastness of Ink Jet Prints Exposed to Indoor Fluorescent Lighting and Window-Filtered Daylight* (1999), does, however, recommend the use of both print density and ΔE_{ab} to evaluate the results. The standard suggests using the density measurement to determine the initial concentrations of the colour test patches, and then to determine any density loss after light fading.

4.3.10 Calculating the damaging effect of wavelength

The relationship between damage versus wavelength D(λ) has already been reviewed in 3.4.6. Saunders *et al.* (1994) suggest an effective way of evaluating the effect of wavelength from data collected on the fading rate of artists' pigments using seven broad-band interference filters. First, he calculated the total exposure of each spectral region studied or the irradiance, H (in watt hours per square metre, Whm^{-2}) with the following function:

$$H = tE_v \left[\sum_{400}^{700} s_\lambda . t_\lambda d\lambda \right] \tag{4.5}$$

Where t is the time of exposure, E_v the visible illuminance in lux ($lumen.m^{-2}$), s_λ the spectral power distribution of the illuminating source in $W.lumen^{-1}$ and t_λ the transmittance of the appropriate filter.

He then selected a suitable exposure limit of 25 000 Whm^{-2} from the collected data (equivalent to fluorescent light exposure (with no UV light) at 50 lux for eight hours per day for about 40 years) and compared the results from the different filters at that particular exposure time. The final results D(λ) were then plotted for wavelength against ΔE_{ab}, and any relationship could then be assessed. This measurement was applied to the data collected from the fluorescent test method.

4.4 Part 3. LIGHT AGEING METHODS

4.4.1 Microscal Light Fastness Tester

This system was the first light ageing method employed for this research. Literature published has shown that results obtained from the Microscal Light Fastness Tester have good correlation with daylight and Xenon Arc light ageing techniques when fading the blue wool scales (Giles *et al.*, 1969, Park and Davis, 1972, Park and Smith, 1974). The light ageing process is also recommended in the BS 1006 (1990) as a method for accelerated light ageing of textiles.

Initially, the high output Microscal MBF/U (Mark IV) lamp was used for testing but the lamp was found to be unsuitable, because it radiated too much heat and the temperature of the samples could not be maintained below 60 °C - 65 °C. The tests were then performed with a Microscal MB/U (Mark 1C R/F) lamp tester. This lamp emitted less radiant heat, and samples could be kept at the temperature stipulated in the BS 1006 (1990) of 40 °C.

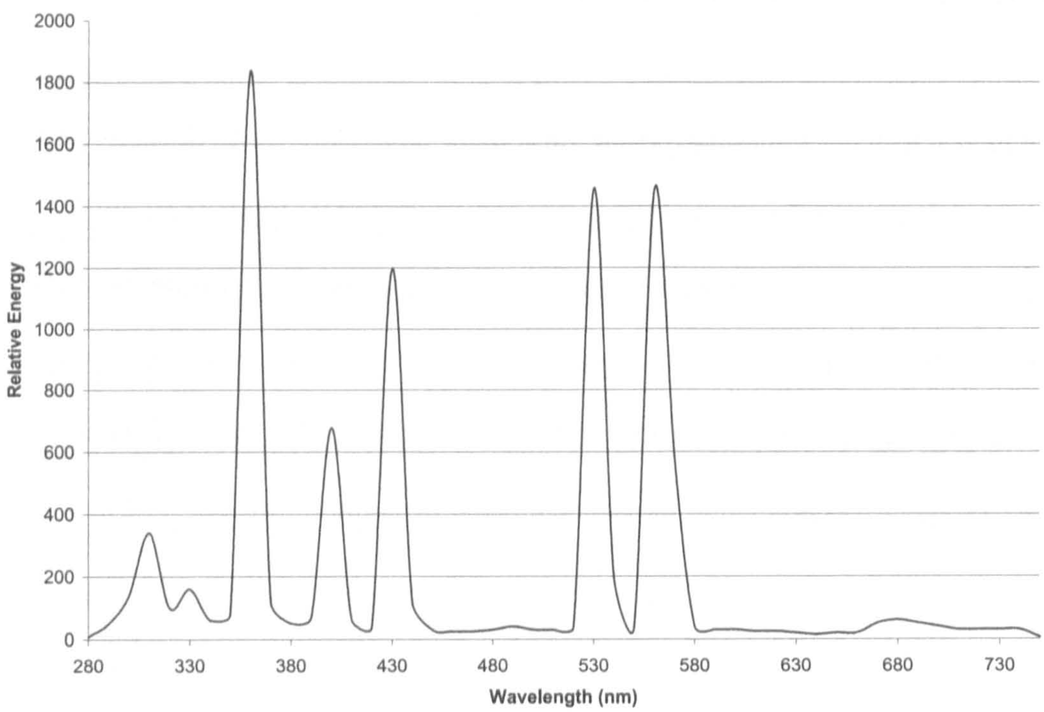

Fig. 4.2 Emission spectra of the Microscal mercury lamp (250 V, 125 W) (MB/U) (Giles *et al.*, 1969).

The Microscal Tester is made up of a large cylindrical drum that surrounds a high-pressure mercury vapour light bulb (employed for street lighting), which emits a steady output of radiant energy (Giles *et al.*, 1969) (see fig. 4.2). Around the drum twelve cells can be suspended at equal distance from the lamp (see fig. 4.3 and 4.5). The cells are made from an oblong stainless steel case with a glass front, and are designed to hold textile or paper samples (10 mm x 50 mm). The cell contains an oblong stainless steel block that is adhered to the sidewalls. A small copper tube runs through the block and allows cooled water to pass through the tube to cool down the cell when it is exposed to the lamp (see fig. 4.3.). The base of the cell is made from an epoxy resin. The base holds a small plastic container that screws into the epoxy resin. The container is designed to hold a saturated salt solution to control the humidity within the cell. Potassium carbonate, K_2CO_3, recommended by BS 1006 (1990) and Giles *et al.* (1969), Park and Davis (1972), Park and Smith (1974), was selected to regulate the relative humidity to 45 %. Each cell is sealed with a rubber detachable lid.

Samples are secured in the cells by use of stainless steel holders. A new design was made to the facia of the holder to allow a larger area to be viewed for ease of colour fading assessment both visually[29] and with a Chroma Meter (see fig. 4.4).

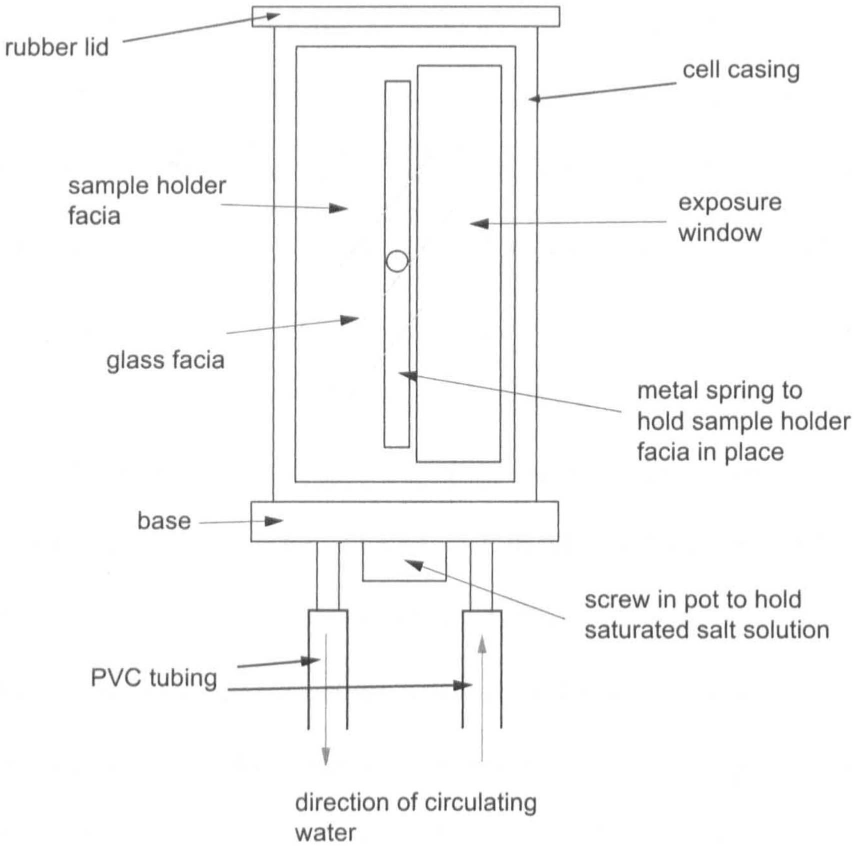

Fig. 4.3 Diagram of the sample cell holder.

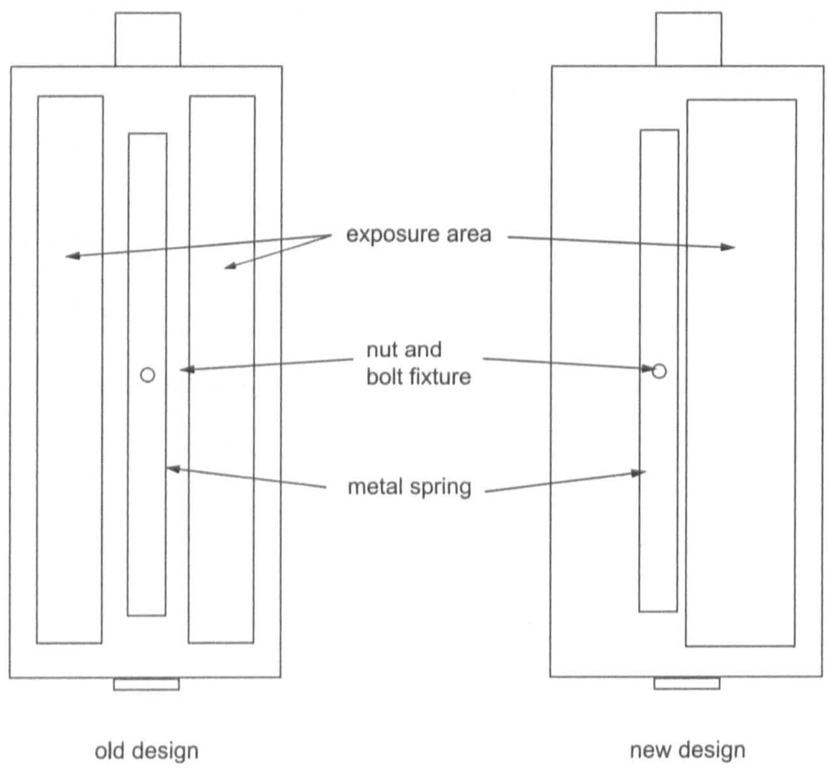

Fig. 4.4 Diagram of the old and new facia design of Microscal sample holder.

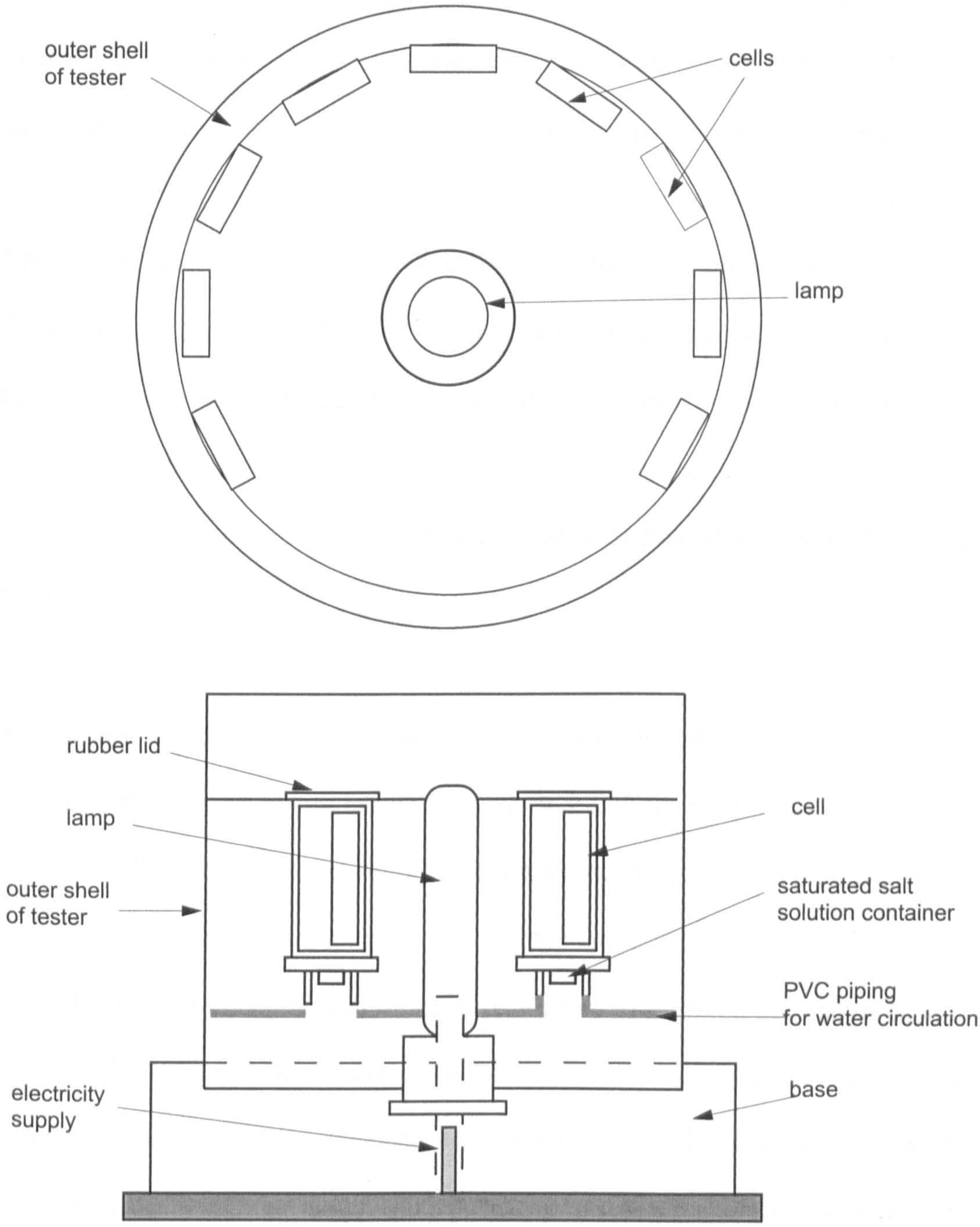

Fig. 4.5 Diagram of the Microscal MB/U Light Fastness Tester.

4.4.2 The Microscal cooling system

An 'Air Cooled Exchanger' manufactured by Microscal was used to cool the cells in the Tester. The device pumps water through small copper piping running through each cell. Small strips of PVC tubing are used to link the cells. The first and last cells are connected by the piping to a water-cooling apparatus. This consists of PVC piping wrapped around a metal frame that allows heat to be lost by convection from the water that has travelled about the system. The cooled water is then circulated back around the cells again. During the summer months, a fan was employed to increase the circulation of the air around the room to help the cooling system maintain the desired cell temperature.

The cooling system developed a number of blockages. Although it was recommended by Microscal that all twelve cells could be used at one time, it was realised that only nine cells could be cooled with the system because the water pump did not have enough power to push water through all twelve cells at once.

Several types and mixtures of water were put through the cooling system as it was found that plain tap water caused lime scale and growth of organic matter in the water after a period of time, even though the system was cleaned regularly. De-ionised water was also tested, but this eroded the copper tubes inside the cells causing the system to block. The problem was resolved by using a radiator cleanser and preserver manufactured by Kilrock Products Ltd. The cleanser flushed the system and the preserver prevented the build up of contaminants.

4.4.3 Environmental monitoring of the Microscal system

The temperature of the cells and the surface temperature of the samples held in the cells was monitored every day for the first month of testing, and then every three to four days to check that the system ran to the specifications set by the BS 1006 (1990) of 40 C (+/- 2 °C). Unfortunately, relative humidity could not be measured, because the size of the cells was two small to insert the measuring device. Therefore, the relative humidity of the test could not be guaranteed, but the cells were cleaned and the saturated salt solutions changed every one or two weeks. The surface temperature of the black ink/toner patch was measured for each sample set after exposure to the tester for one week to record the black panel temperature[30].

A new lamp was inserted into the Microscal Tester before any testing commenced, and was left on for 100 hours before light ageing, since research has shown that the spectral distribution of the lamp can differ significantly with time (Cannell, 1983). Microscal recommends that the bulb should be replaced after every 2000 hours when the light loses 25 % of its efficiency[31], but the testing period fell short of this limit. The average lux level reaching each cell was recorded at specific intervals during the testing period[32]. The level of illuminance emitted by the lamp was much higher than the recommended light levels by Saunders *et al.* (1996) for the reciprocity principle of light fading to apply (see 3.5.2). This factor is considered in the 'Discussion of the Results' section.

4.4.4 Colour measurement of samples exposed to the Microscal Light Tester

All samples sets were exposed alongside a blue wool scale that was used as a reference (see 4.3.8). The position of the blue wool scale was moved around the tester for each change of sample set. This procedure was used to monitor any difference in the fading rate of the lamp around its circumference. Samples were exposed until one of the primary ink colours had faded to at least $\Delta E_{ab} = 3.4$; which is approximately equivalent to the BS 1006 grey scale of 3 (see 4.3.8). CIELAB measurements were recorded frequently during the tests. Before measurements were taken, the lamp was switched off and the samples were left for half an hour to cool down before colour assessments were made.

4.4.5 Natural light ageing methodology

Following the procedure discussed in B.S 1006, B01 (1990), print samples were exposed to light from a south facing window held at an angle that is perpendicular to the sun at the particular position in the world that the experiment is taking place. The Greenwich observatory situated approximately 4 - 5 miles from the Camberwell College of Arts, has measured this angle to be 51°. Therefore, a frame was constructed to hold the board at an angle of 50°. The sample exposure area was made from a wooden painted board (500 mm x 500 mm) fixed to a metal frame (see fig. 4.6). The board was painted white using ordinary emulsion paint[33].

Two sets of each type of sample were exposed - one sample with an UV filter held in front of the printing and one sample left unfiltered. The print specimens were attached to the wooden board with map pins. The samples were exposed to daylight for a period of six months from April to September[34]. The rate of fading of the samples was assessed every one or two weeks with the Chroma meter. Two blue wool scales, one with an UV filter placed in front of the scale the other left unfiltered, were exposed alongside the specimens, and assessments were made at the end of the test using the BS 1006 (1990) grey scale. The total lux hours of the exposure were recorded with an Elsec Integrating Light Meter, Type 790. The temperature of the testing environment and the relative humidity was constantly monitored with a thermo hygrograph. No measures were taken to reduce pollutant gases from the surrounding environment. Once testing was completed the fading rate of the samples and the Blue Wool scale were compared with the results from the Microscal to determine if there was any correlation.

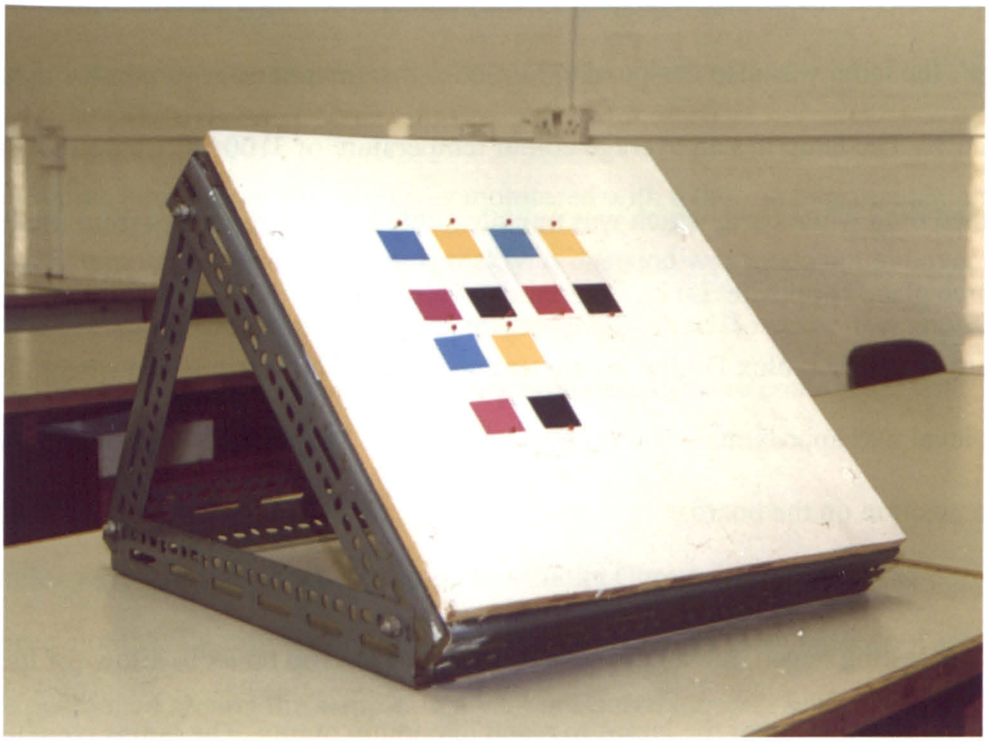

Fig. 4.6 Photograph of natural daylight sample exposure stand.

4.4.6 Tungsten halogen light ageing

Halogen lamps are a form of artificial light frequently found in art galleries and museums. Therefore, it was decided to test the effect of this type of light using a relatively low illuminance level under normal room conditions[35]. Samples identified in the 'Natural' and Microscal tests as being very sensitive to light (less than blue wool rating of 3) were examined to see if exposing the prints to an illuminance of a 1000 lux would lead to noticeable fading over a reasonable short period of time of three months.

Two Osram Decostar IRC (48865 Flood, 24° beam angle) tungsten halogen lamps were used for the testing. The lamps incorporated a UV filter patented as 'UV stop', the lamp was also designed to minimise the amount of heat radiated by up to 66 %. The lamp has an average colour temperature of 3100 °K. Samples were pinned onto white card, which was mounted onto a wall two meters from the light source placed opposite. Lux measurement were taken of the light falling onto the board with a Mavolux Digital lux meter and the position was marked where the lux level was approximately 1000 lux (+/-100 lux). The samples were then pinned into position on the board.

Before testing began, the lamps were illuminated for 100 hours to allow for the spectral distribution of the lamps to reach maximum output. The lamps were used for a period of three months and the bulbs were changed approximately every 3000 hours.

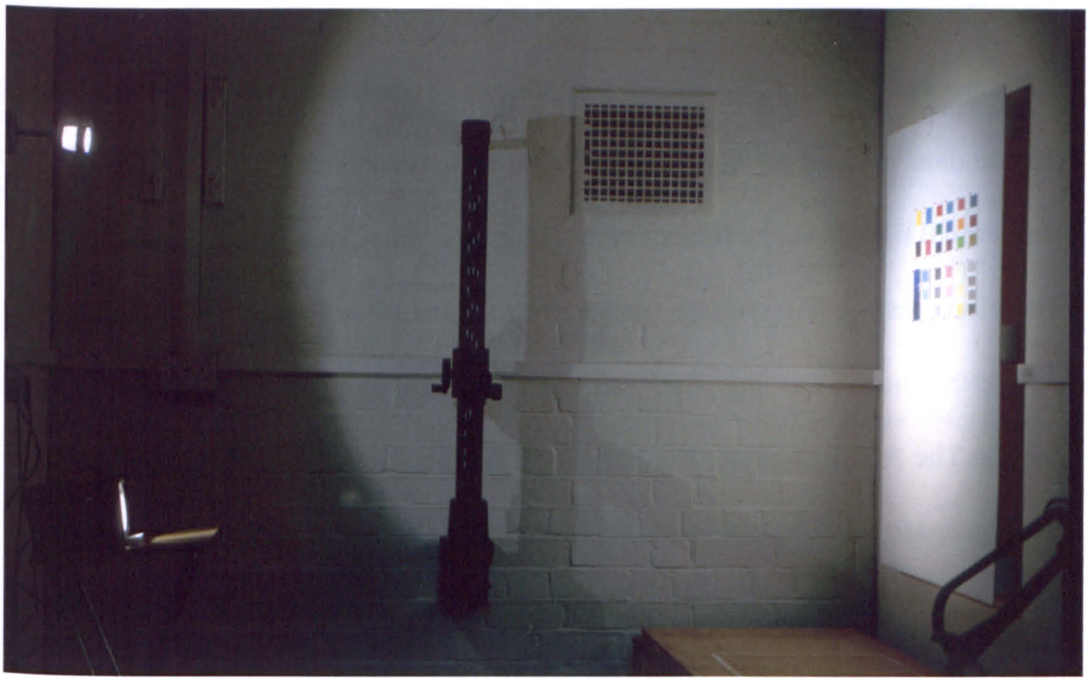

Fig. 4.7 Photograph of tungsten-halogen light fastness test exposure.

The relative humidity of the room was monitored with a thermo hygrometer, and the room temperature was measured weekly. A decision was made not to cover the prints because the lamps already contained a UV filter. However, this approach meant that any pollutant gases in the surrounding atmosphere could react with the samples.

Samples were measured weekly using the Minolta Chroma meter, over the period of three months. To monitor the rate of fading of the lamps three blue wool scales were positioned around the sample area, and measured together with the samples. The samples were moved around in a set sequence every week to allow even illumination.

4.4.7 Fluorescent light ageing methodology

Many museum and gallery testing laboratories have adopted fluorescent light as the standard method for light ageing[36]. The main reason for this choice is that fluorescent light is very efficient and the lamps emit very little IR radiation. Therefore, testing temperature can be controlled close to normal room conditions. The ANSI and ASTM have both published standard methods for fluorescent light testing. The ANSI standard, the ANSI/NAPM IT9.9-1996 *Stability of Color Photographic Images – Methods for Measuring* clearly states that the testing methodology is only for photographic material and not for digital hard copy printing[37]. The ASTM has several standards illustrating a procedure for fluorescent light ageing, two of which are directly aimed at the assessment of the light stability of digital printed materials: F1945-98 *Standard practice for determining the lightfastness of ink jet prints exposed to indoor fluorescent lighting*; F1946-98 *Standard practice for determining the lightfastness of ink jet prints exposed indoor fluorescent lighting and window-filtered daylight*[38]. However, these particular standards do not fully describe the specifications required for light fast testing and only give references to other standards. The various specifications that are determined for fluorescent light fastness testing by the research departments from the Image Permanence Institute (IPI), Rochester Institute of Technology, New York, the Tate Gallery, London, Wilhelm Imaging Research, Iowa, USA, National Gallery, London are reviewed in table 4.2. Also listed, are the specifications published by the ANSI/NAPM IT9.9-1996 *Stability of Color Photographic Images – Methods for Measuring.*

Table 4.2 Specifications for fluorescent light fastness testing published by various research institutions and standards.

	Wilhelm[39]	*ANSI/NAPM IT9.9-1996*[40]	*IPI*[41]	*Tate Gallery*[42]	*National Gallery*[43]
Lamp Type	Cool white Fluorescent[44]	Cool white Fluorescent	Cool white Fluorescent	Phillips TLD94 58W Daylight	Thorn Artificial Daylight
Lux Level (klux)	13.5	6	50	13	10
Experiment Duration (Yrs.)	3	0.5 – 1	Not Specified	Not Specified	Not Specified
Temp (°C)	23	24 (± 2)	20	+5 above ambient	32
RH (%)	60 (at sample plain)	60 (± 5)	40-50	10 % lower than ambient	40 (± 5)
Additional conditions	High-velocity forced air-cooling, UV filtered.	None Specified	None Specified	UV filtered	Ventilated chamber, UV filtered

The fluorescent light tests were the final light ageing method employed in this study. The method was used because environmental conditions such as temperature, relative humidity and illuminance could be controlled and reproduced more easily than in the other light ageing methods. The aim of the investigation was also to study the effect of specific bands of wavelengths from the visible portion of the electromagnetic spectrum, to assess whether the print samples, which had been shown to be very sensitive to light in the previous light tests, were particularly responsive to a particular band of wavelengths.

4.4.8 Construction of fluorescent light box

An oblong metal Dexion frame (1440 mm x 103 mm x 380 mm) was constructed as the support structure for the light ageing apparatus. Two Tamlite battens (TL236) fitted with two universal reflectors (TLUR4) to direct the light onto the samples were used to hold four Phillips 'TL'D/965 fluorescent light tubes. Phillips

TL'D/965 fluorescent tubes were chosen for this study, as the light they radiated was sufficient in most of the wavelengths of the visual part of the spectrum required for the investigation (see fig 4.8 for spectral curve). The fluorescent cases were fitted facing downwards at the top of the frame. A shelf was then built underneath the fluorescent lights to support the samples by bolting two support brackets to the frame. The construction of the Dexion frame allowed for the position of the shelf to be moved up or down by moving the brackets. Lux measurements were taken at various distances from the light source to locate the position where the samples would receive approximately 6 klux units, and the shelf was then fixed into that position (see fig 4.9 for diagram of apparatus).

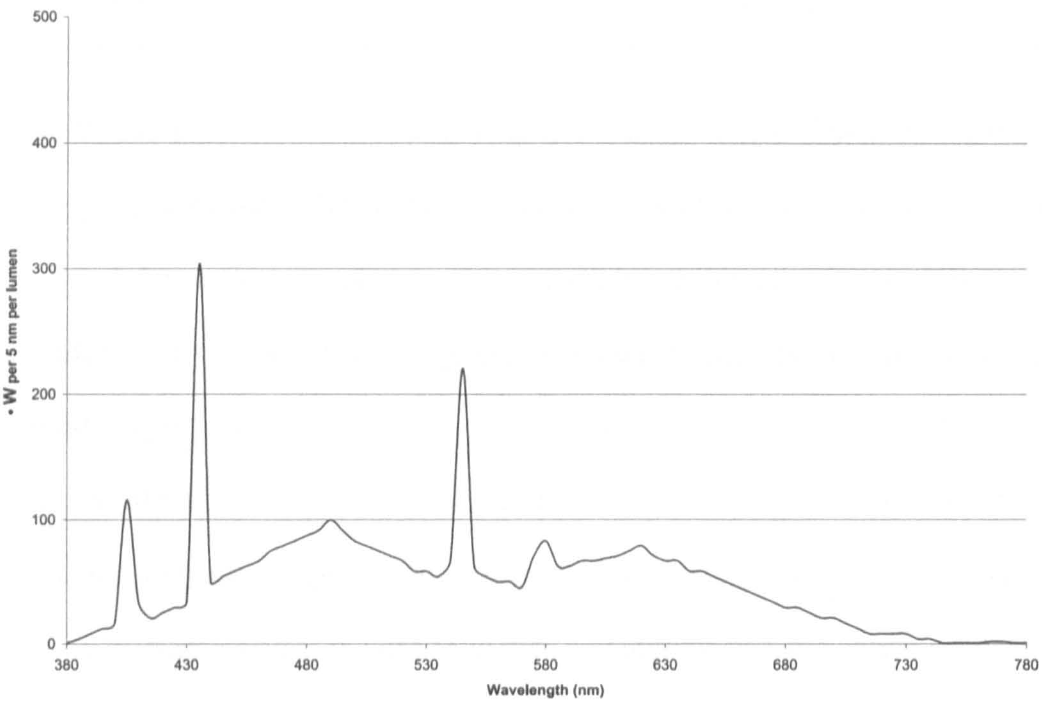

Fig. 4.8 Spectral distribution graph of the Phillips 'TL'D/965 fluorescent light tubes.

A box (1010 mm x 455 mm x 75 mm) was constructed to house the samples from acrylic sheets 4 mm in thickness. The edges of the box were sealed with polymethylacrylate. The polymethylacrylate was used to dissolve small filings of the acrylic sheet. This produced an adhesive, which was then used to adhere the pieces together. To allow access, the lid of the box was not attached (see fig. 4.9 for diagram). All the interior walls of the box except for the lid were lined with aluminium foil ensuring the maximum amount of light was reflected onto the samples[45].

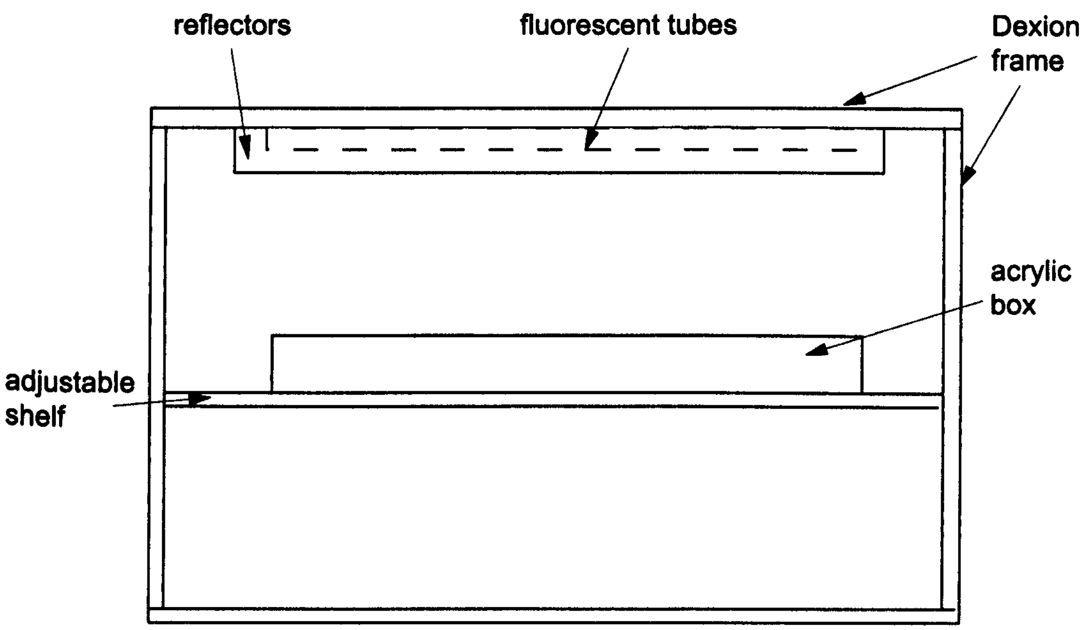

Fig. 4.9 Diagram of the fluorescent light fastness tester.

To reduce the level of air exchange in the box, two different types of draught excluder were fitted to the lid and top edges of the sides of the box. When the lid was closed, the draught excluder strip of the top edges fitted in between the double edging strip placed on the lid (see fig. 4.10). It was decided to control relative humidity to approximately 60 %. This value of humidity is recommend for light testing by the ANSI/NAPM IT9.9-1996 (1996), Wilhelm *et al.* (1994), and IPI[46], and is within the range of humidity values recorded in museums and galleries around Europe[47]. After trying different humidity controlling methods, it was decided to use saturated magnesium acetate solution held in four small containers at each corner of the box[48]. The magnesium acetate solution is designed to control humidity to 65 %, but due to the large volume of air within the box, RH was maintained at approximately 59 % to 60 %, although this value dropped after three weeks of testing and humidity levels maintained an average of 55 % (see 5.5.2). Relative humidity (RH) was monitored with a hygrometer that had been calibrated before testing, and temperature was recorded with an electric thermometer. Both readings were recorded regularly every week.

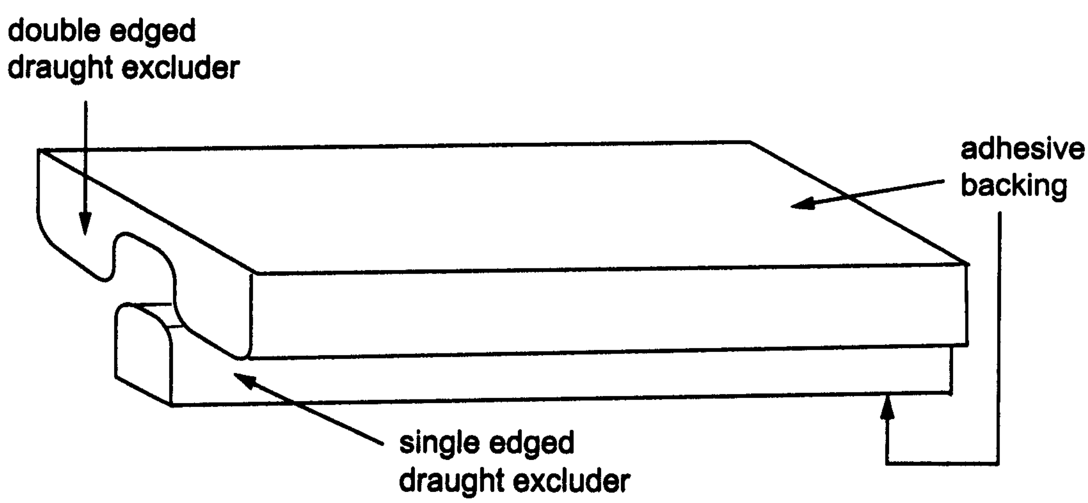

Fig 4.10 Diagram to show the how the level of air exchange inside the fluorescent light exposure box was reduced using two different types of draught excluder.

The samples were moved around the box in a set sequence every three to four days so that they could be radiated evenly (see fig. 4.11 for diagram for sequence)[49]. Before any testing commenced, the lamps were left on for 100 hours since research has shown that the spectral distribution of the lamp can differ significantly with time[50]. One tube was also replaced every four weeks[51]. Light levels were measured with a Lutron LX-101 lux meter and lux hours exposure obtained by calculation.

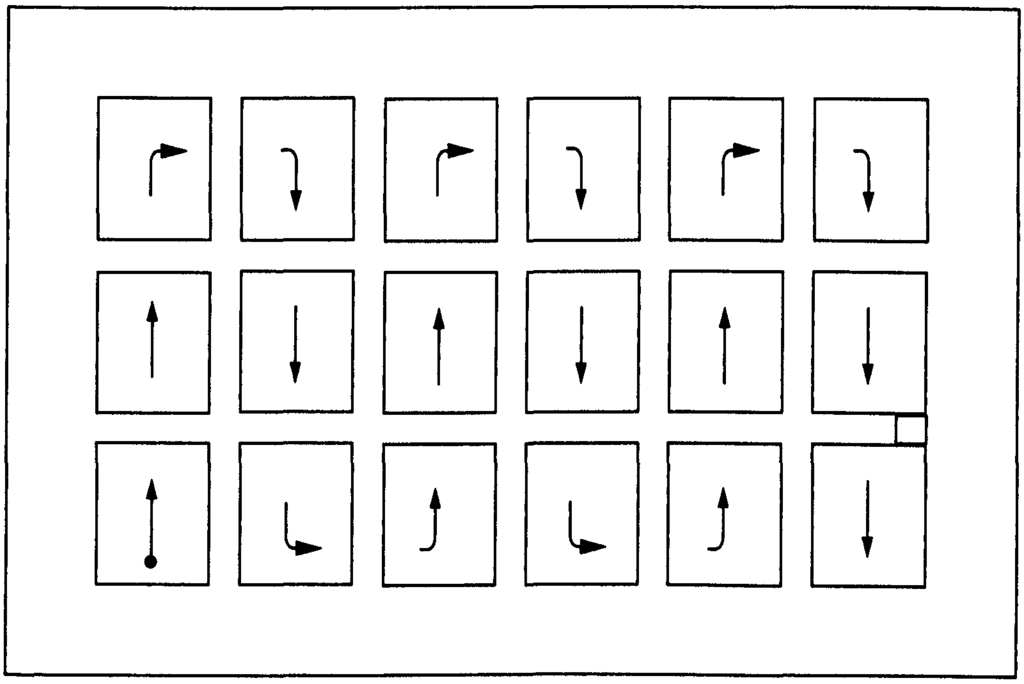

Fig. 4.11 Diagram to show the sequence of movement of the samples during the fluorescent light fastness test.

4.4.9 Colour measurement

Samples were measured weekly with a Minolta Chroma meter to obtain CIELAB readings, and any difference was calculated using the ΔE_{ab} equation (see 4.3.6). A set of samples of just the four separate ink colours CMYK were covered with black card and exposed alongside the other samples, for the dark control. The surface temperature of the card was also recorded to assess the black panel temperature.

4.4.10 Photochromism

Analysis of the results showed that some of the inks with a selection of the print samples demonstrated very uneven fading rates (see 5.6 and figs. 5.17, 5.22, 5.28, 5.29, 5.30, 5.34, 5.40, 5.41, 5.42 and 5.43). The inks appeared to fade on exposure to light with the first and/or second measurements, but then subsequent measurements revealed that the samples seemed to recover some of their colour and/or strength. Further readings would record a similar pattern of losing colour or strength and then a reversal of the change to some degree. This phenomenon has been recognised for certain dyes and has been termed Photochromism (see 6.2.4). The British Standards Institute have published a test to determine its occurrence with textile samples called BS 1006, B05, *Detection and Assessment of Photochromism* (1990), and the procedure for this experiment was undertaken for the print samples that showed uneven fading rates.

Testing was performed with the Microscal Light Fastness Tester. Print samples of the particular inks were placed in the tester cells and exposed to light under the conditions specified in 4.4.1. The samples were measured every day with a Minolta Chroma meter CR 300 until each sample showed a change in fade of ΔE_{ab} of 1.25 - 2.09[52]. After the samples had reached this degree of fading they were exposed to the lamp for another 24 hours. The samples were then measured again and if the change in ΔE_{ab} was double the change recorded the previous day, the samples were then placed in dark storage in an environmentally controlled room for 24 hours and then colour measurement were taken once more. Additional to the test discussed in BS 1006, B05 (1990), the samples were also measured 10 minutes, 30 minutes and 1 hour after the samples were taken out of the tester and placed in dark storage.

4.4.11 Colour gamut graphs

The inverse relationship between colour gamut (the range of colours that can be printed) of an ink set and light fastness has been discussed by Jürgens (1999) (see 3.7.7). The colour gamut of each of the sample sets was plotted using CIELAB colour measurements taken from the colour patches that were composed of the CMY inks printed separately and where two of these inks were printed together in different ink concentrations (see 4.2.3). The graphs were then compared to the results from the light fast investigation to examine if this relationship occurred.

4.5 Part 4. CONSERVATION AND ANALYSIS TESTING

4.5.1 Thermal ageing of coated papers

Stability results obtained from thermal ageing tests are known to be even more controversial than light-ageing data, because of the extreme temperature and humidity conditions involved (Bansa, 1992, Porck, 2000). High temperatures in particular can lead to chemical reactions that would otherwise not occur in normal circumstances (Feller, 1994). The Arrhenius test method, which uses a number of different temperatures, is considered to give results that are more accurate but requires a much longer and complicated testing period and could not be performed with the facilities at Camberwell College of Arts (Smith *et al.*, 2000, Wilhelm *et al.*, 1994, Porck, 2000, ANSI/NAPM IT9.9, 1996, ASTM F 2035-00, 2000). Recently, there have been a few investigations published discussing the long-term stability of ink jet prints in storage, with the application of thermal ageing (Smith *et al.*, 2000). The test methods have shown that the ink jet coated papers yellow readily, and that the inks are susceptible to humidity conditions of 80 % and higher (Robb, 2000). The tendency for a paper to yellow may not become evident in the light ageing tests because reaction of this type can often be bleached by the light source (Mailly *et al.*, 1997, Feller, 1964). Therefore, it was decided to use thermal ageing technique to see if the papers in question had a tendency to yellow under thermal ageing conditions.

A selection of the coated ink jet substrates and electrophotographic papers used with the light ageing tests were prepared and their colour measurements recorded using both the Chroma meter and Xrite spectrophotometer. Ten CIELAB and six spectral measurements of each paper were documented from different areas around each sheet so that an average could be obtained. Samples were then aged in a thermal ageing oven for a period of three weeks, with the conditions set to 80 °C and 60 % RH (Bansa,1992).

4.5.2 Cold extraction

The pH of all the papers was determined by cold extraction before and after thermal ageing. One gram of each paper cut into small pieces was measured out on an electronic balance, and place in a 100 ml beaker. 20 cm of freshly boiled out distilled water was added to the beaker, and a glass rod was used to get the paper well saturated. A further 50 cm of freshly boiled-out distilled water was added, and the beaker was left to stand for one hour. The pH of the resulting solution was measured with a pH probe and meter. The process was repeated for a further three times: another set of the same papers to record an average; two sets of the papers after thermal ageing.

4.5.3 Transfer of printing

The following method, to test for the transfer of print, has been developed from the method described in BS ISO 11798 (1997). The method discussed below differs from the experiment described in BS ISO 11798 because some of the equipment specified in the test was not available at the time of testing. In the test, it stipulates that a pressure of 7 kPa should be applied to the stack of papers, but there was no equipment available at the time to measure this value.

A sample of the four primary colours was selected from each sample set and the papers were divided into three groups. The samples from each group were stacked one on top of the other. Pieces of bond paper cut to the same size as the samples, were placed in between each sample and the top sample was covered with the paper. The three stacks were then put in between two wooden boards and a 2 kg weight was placed on top. The stacks were then placed into a thermal ageing oven set at 80 °C and 60 % RH for a period of six days. After this period the samples were removed from the oven and left to cool for 15 hours, and then the papers were then separated and examined for changes.

4.5.4 Conservation treatments

A separate colour patch layout was designed for the conservation treatments (see 4.2.2 C). The following treatments were then performed and their effectiveness was observed and evaluated.

4.5.4.1 Mechanical dry cleaning

Mechanical dry cleaning is a useful treatment to remove loose dirt from the surface of the substrate (Sterlini, 1995, AIC, 1992, Banks, 1969). The following four different cleaning methods were employed: latex sponge; draft cleaning powder; Mars plastic eraser; cotton wool sponge. Each cleaning device was gently applied across the surface of the samples. Observations were then made both visually and under magnification (X 10) to assess and any physical damage that may have occurred.

4.5.4.2 Humidification

The humidification process allows moisture to slowly enter a substrate by capillary action, to relax any cockling, creases, and to help remove dirt and degradation products (Stibbon, 1993). The treatment is particularly suitable for objects that are otherwise sensitive to other moisture treatments.

All the samples were placed in a large acrylic box, which contained a sheet of blotter that had been previously dampened with water and a piece of capillary matting laid over the top, that allowed the moisture from the blotter to slowly enter into the papers. The box was covered with an acrylic sheet to maintain a humid environment inside the box, and constant checks were made to the samples to monitor any spreading of the inks. Samples were left in the chamber for a period of four hours until the papers had become evenly damp.

CIELAB measurements were recorded before and after testing, and observations were made both visually and under magnification (X 10).

4.5.4.3 Washing

Aqueous treatments in conservation can aid the removal of staining, discolouration, dirt and degradation products, increase the alkalinity of the substrate, and can rejuvenate the bonds between molecules of the paper structure (AIC, 1990, Lienardy *et al.*, 1990). All wash treatments performed at the college use ordinary tap water, as the water has been previously tested by the college and found suitable for the process.

First a small amount of water was applied to the samples by the aid of a fine brush, the area was then pressed with blotting paper and the sample and paper was examined to see if the ink was fugitive. This process was repeated twice, adding slightly more moisture at each stage. Samples that showed to be wet fast after the first test were then sprayed with water to allow for even saturation and then submersed in a water bath for a period of five minutes and observed for any changes. The samples were then removed and pressed dry between two pieces of blotting paper, and re-examined for fugitivity. Any samples that were found to be still wet fast were re-submersed in the water bath for a further 30 minutes and examined again.

4.5.4.4 Industrial methylated spirits (IMS) (95 % (v/v) ethanol, 5 % (v/v) methanol)

Industrial methylated spirits (IMS) is a common solvent used in conservation. It is added to water to improve the wetting ability of a wash treatment, or can be used instead of water to dissolve substances (stain removal, poultice, backing removal, etc.) if an object is found to contain a colourant that is fugitive in water but not in IMS (AIC, 1990, Lienardy *et al.*, 1990, Hey, 1979).

The samples were laid onto a sheet of blotting paper and a small droplet of IMS was applied to the material with a pipette. Any changes to the samples were recorded and then the area was then pressed with blotting paper and the sample and paper was examined to see if the ink was fugitive. The samples were then left to dry between two pieces of blotting paper, and after drying further examinations were made with the aid of a microscope.

4.5.4.5 De-acidification

Paper can become brittle and discoloured if acidic forming substances are present in or on the object such as lignin, rosin size, or a acid forming ink such as iron gall. Aqueous de-acidifying agents such as calcium hydroxide ($Ca(OH)_2$) solution can be added to a wash treatment or applied to paper to improve the objects long-term stability by increasing the alkalinity of the substrate and limiting the formation of acidic forming substances that can be detrimental to the object's structure and appearance (Bansa, 1998, Daniels, 1987, 1980, Hey, 1979).

The samples were laid onto a sheet of blotting paper and a small droplet of calcium hydroxide diluted with water (1:5) was applied to the material with a pipette. Any changes to the samples were recorded then the samples were then left to dry uncovered. After drying further examinations were made with the aid of a microscope.

4.5.4.6 Tear repair

Coated ink jet papers have very different characteristics than previous types of manufactured paper. It was therefore considered important to test how the paper would react to a repair treatment.

Each sample was torn in half and adhered back together with a slight overlap using a freshly prepared batched of wheat starch paste applied with a brush. The sample was then pressed in between two sheets of Bondina[53] and blotting paper to soak up any excess moisture and to let the repair dry flat (AIC, 1984, Jones, 1978). After drying visual observations were recorded of the samples and pressing papers, and the samples were also examined under a microscope.

4.5.5 Identification

The wide variety of digital printers and manufacturers available and the large difference in the stability characteristics of these prints signifies that identification of the print process, inks and papers is an important procedure for the preservation and exhibition of these objects. The name 'ink jet' can also be used as a generic term for all forms of digital printed fine art material, although there is a substantial difference between various types of digital printers.

An extensive survey and introductory guidelines for the classification of digital prints, inks and papers has recently been published by Jürgens (2000). He gives an excellent overview of the range of the print processes, inks and papers, and suggests some methods of classification by observation techniques.

4.5.5.1 Visual examination

Visual assessments were made under ambient lighting conditions, with the aid of raking and transmitted light and with a stereomicroscope to assess any particular characteristics of the samples that could help with the identification process. Photographs of a section of the samples were also taken under X 10 magnification to record any distinguishing features of the printing process.

4.5.6 Spot tests

A selection of chemical spot tests were investigated to test for the presence of gelatine, starch, mechanical wood pulp and lignin in the various ink jet and electrophotographic papers studied. The tests were performed to help to understand the composition of the papers, because the light fastness of the printed material would vary when on different papers. The method of each spot test is described below.

4.5.6.1 Identification of Gelatine

A sample of paper was place into a test tube (3 mm x 3 mm). A drop of sodium hydroxide solution (4 M) was added to the tube, using a pipette. The tube was heated in a beaker of boiling water for five minutes. The test tube is then removed and cooled. One drop of copper sulphate solution (1 M) and one drop of hydrogen peroxide solution (20 vol.) were then added to the test tube. Effervescence of the solution in the test tube occurred and once the reaction had settled down, the test tube was returned to the beaker of hot water. The liquid in the bottom of the test tube should be blue. The test tube is then heated for a further three minutes in the boiling water. The test tube is then cooled and three drops of sulphuric acid (2 M) are added followed by two drops of Ehrlich's reagent. Finally, the test tube is heated for a further two to ten minutes in boiling water. If gelatine was present, a pink coloration developed within this time (Collings, 1976).

4.5.6.2 Identification of Starch

A sample of paper was place onto a white tile. A drop of the solution one part of tincture of iodine to four parts of distilled water was added to the paper using a pipette. If starch was present, the sample turned deep blue (Feigl, 1975).

4.5.6.3 Identification of Mechanical Wood Pulp

A sample of paper was place onto a white tile. A drop of a reagent containing aniline sulphate (1 mg) dissolved in distilled water (50 ml) and a drop of sulphuric acid was place onto the sample using a pipette. If mechanical wood pulp was present, the sample turned yellow (Feigl, 1975).

4.5.6.4 Identification of Lignin

A sample of paper was place onto a white tile. A drop of phloroglucinol (2 mg) dissolved in Industrial Methylated Spirits (50 ml) was added to the sample with a pipette. If lignin was present, the sample turned to a deep pink (Feigl, 1975).

4.5.6.5 Identification of Azo Dyes

A test for the detection for azo dyes in the ink jet print samples was also investigated (Feigl, 1975). The test is designed for liquid inks, but since the ink jet inks were not available in liquid form, the procedure was carried out using the samples printed on the Whatman watercolour paper (250 gsm). The Hewlett

Packard print samples were tested on the Hewlett Packard Heavy Weight Coated paper (130 gsm), because specimens were not available on the Whatman paper.

For the test, a sample piece of the sample was placed into a micro test tube, and a drop of 1:10 hydrochloric acid and several small pieces of zinc were added. The sample was then left for a period of 5 minutes to allow the reduction reaction to occur. The reduced solution is then placed on filter paper, allowed to soak in, and then dried briefly in a thermal ageing oven. The spot is then treated with a saturated benzene solution of p-dimethylaminobenzaldehyde. A red to yellow fleck indicates a positive response (Feigl, 1975).

4.5.7 CHROMATOGRAPHY

Thin-layer chromatography (TLC) was used to analyse the composition of the inks. Small samples (2 mm x 2 mm) of the CMYK inks from each ink set were cut out with a scalpel and were adhered ink side down near to one of the edges of the TLC paper with methyl cellulose paste. The paper was then suspended over a dish containing a combination of butanol, industrial methylated spirits and water (4:1:1), with the edge of the paper with the samples just touching the solvent. The paper was left to soak up the solvent for one hour, and was left to dry before assessment.

4.5.8 SCANNING ELECTRON MICROSCOPE (SEM)

Scanning electron microscopic images were obtained from JEOL Ltd., a Japanese company who manufacture SEMs. The SEM is used to observe microscopic objects over a wide magnification from X 10 to X 1,000,000. The SEM has a larger depth of field than an ordinary stereomicroscope and allows clear photographic images to be recorded of the magnified material.

Two of the Epson Pro 9000 ink jet coated papers were analysed using the SEM – the Photo Glossy (190 gsm) and Presentation Matt (172 gsm) papers. They used the JSM-5600LV SEM for the analysis. JEOL were also able to perform X-ray analysis of the two papers, using an Energy Dispersive X-ray Spectrometer (EDS). The EDS can identify and quantify the elemental composition of a sample.

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[1] The Tate Gallery, London, The Victoria and Albert Museum, London, The Alan Cristea Gallery, London, The Corville Gallery, London, Museum of Modern Art, New York have all exhibited and/or collected digital artwork and were contacted during the research.
[2] During interviews with Jason Nicoll at Seiko Epson Corporation Ltd. and Chris Slemel of Canon Ltd. both said that the market for ink jet printers changes every six months, with the introduction of new and improved products.
[3] Lyson are the manufacturers of the Lysonic and Fotonic ink sets for Iris and Epson printers. Light fastness ratings for these inks have been tested by Wilhelm Imaging Research Inc. to be higher than the inks manufactured by the original companies (www.wilhelm-imaging.org).
[4] When Lyson was visited to obtain printing samples for the research, their two Iris printers were no longer in use by the company, and samples could not be obtained on these machines.
[5] Lyson were visited in May 1999, to obtain print samples for the research. The company were running tests for their new inks to be marketed for the Epson Pro 9000 printer on a Mutoh Falcon RJ-4000 large format ink jet printer. The Epson Pro 9000 was to be released later that year and was therefore unavailable at the time, but the Mutoh Falcon RJ-4000 printer employed exactly the same print engine as the Epson Pro 9000 printer. Therefore, samples were obtained from this system, but the prints were comparable to the results achieved with the Epson Pro 9000 printer.
[6] Sample size is important for visual evaluation, as smaller samples will give less contrast and less severe assessment. Jaeckel *et al.* (1963), p. 717.
[7] "*Green, red and blue colors are obtained by printing sequentially the primary colors on each other ... these colors are rendered by mixtures of dyes that frequently show an increased fading rate due to a photochemical effect known as catalytic fading of dye mixtures. In most reported cases, the lightfastness of cyan, violet and red dyes deteriorate when a yellow dye is added. Catalytic fading is especially strong in green images rendered by mixtures of yellow and cyan dyes.*" Vanmaela (1995), p. 298.
[8] Colour management software is needed to convert the information from the computer monitor using the additive colour primaries (RGB) to the printer, which uses subtractive colour primaries (CMYK). The colour software can alter the way the ink is printed on the page.
[9] "*Fine Art Trade Guild's printing standards require a minimum paper thickness of 250gsm*". Ruston (1999), p. 30.

[10] Many of the original Giclée prints were produced on printmaking papers such as Somerset Velvet and Arches Cold Press in particular (Wilhelm, 2000). Many of the artists involved with the *Integration of Computers within Fine Art Printmaking* project (see 2.1) based at Camberwell College of Arts also preferred to use traditional papers.
[11] Linting can occur with un-sized or lightly sized papers with electrophotographic printers, which can affect the print quality of the machines. Many of the large format Hewlett Packard printers do not allow sheet fed paper through their machines. Instead Hewlett Packard supply roll fed paper for printing.
[12] Advised by Boris Pretzel, Conservation Scientist, British Museum, during meeting at the Conservation Scientists' Group Meeting, University of East Anglia, Norwich, 17/3/98.
[13] BS EN 20187 Paper, board and pulps – Standard atmosphere for conditioning and testing and procedure for monitoring the atmosphere and conditioning of samples (1993) states that the conditioning environment should be maintained at 23°C ± 1°C and 50 ± 2 % RH for a minimum of four hours. Although atmospheric conditions used for this investigation were not exactly the same as specifications of the standard, the environment enabled all the samples to be equally acclimatized.
[14] P. 38.
[15] The spectrum of the carbon arc light source contains a lot of UV light that is not present in indoor situations. Results from these tests have not correlated well with natural conditions (Feller, 1994).
[16] Glass, depending on its thickness cuts off UV radiation below 310 nm. Sinclair (1997), p. 13.
[17] Color Learning Curve Data Facts No. 005, Datacolor International, www.datacolor.com/meters.htm, 11/08/99, p. 2.
[18] Gilchrist *et al.* (1999), p. 5.
[19] Gilchrist *et al.* (1999), p. 6.
[20] The Society of Dyers and Colourists Annual Report (2000), p. 19.
[21] The blue wool scales are composed of particular dyes that were selected so that each cloth would fade at approximately half the rate of its next lower number in the series. The most permanent is eight, the least permanent is 1. The rate of fading is virtually linear over a wide range of practical exposure conditions. Feller (1978), p. 73.
[22] Standard 4 is much faster to standard 3 in fluorescent exposures; standard 6 is slightly faster than 5 in fluorescent exposures, and standard 5 is appreciably faster than 4 in daylight exposures. Jaeckel *et al.* (1963), pp. 713-714.
[23] The standard suggests checking the specimens frequently, and when the subsequent grey scale fade contrasts are achieved of 4-5, 4 and 3, the sample should be compare to the reference blue wool scale and the number of the equivalent faded standard should be recorded. This method continues until the samples reach grey scale fade of 3 or until reference 7 fades to a contrast equal to grey scale grade 4 before the specimen does. BS *1006* (1990), Amendment 3 (1995), p. 4.
[24]For assessment of the fading contrast of the Blue Wool standards, it is better to have four assessors rather than 1. Jaeckel *et al.* (1963), p. 703.
[25] Values were obtained using the ISO 105:A05 conversion equation for ΔE_{ab} to equivalent grey-scale rating. Smith (1997), p. 192.
[26] Blue wool 8 has never been known to fade sufficiently for accurate measurement. McLaren (1956), p.90.
[27] The grey scales consist of nine pairs of grey patches. Each patch contains two panels of grey tones, placed next to each other. Every patch compares a standard grey panel (established at a Munsell neutral value of 4.0) to a either an equally identical grey panel (signifying no contrast), or to panels of progressively lighter tones. The 9 pairs of grey-painted papers are mounted on a black-covered slide-rule-like device with a window through which one pair at a time can be observed. Smith (1997), pp. 185-186.
[28] "*The printing industry has adopted the 5000 degree Kelvin lighting standard developed by the ANSI. 5000 °K was selected because it is a mean between daylight and incandescent light. 5000K lighting is appearing under a compromise situation that attempts to approximate the middle range of the visible spectrum. Therefore, colour that looks good under 5000K will look acceptable under most light conditions. In addition, many light sources suffer from a discontinuous spectrum (fluorescent), meaning that the lamp's spectral output is not uniform for all colours – although the lamp's light appear white*". Eckstein (1991), p. 18.
[29]"*Increasing the sample area for assessment, increases the ease but not the accuracy of assessment*" Jaeckel *et al.* (1963), p. 713.

[30] "*The black panel thermometer measures only the maximum surface temperature that can be reached by any specimen; specimens of lower visible and/or infrared absorption characteristics will be much lower temperature*". McLaren (1963), p.618.
[31] Microscal states in the literature that the lamp deteriorates after 2000h of use, by approx. 20-25%. Operating Instructions for the Light Fastness Tester Mark 1C and Mark 1C R/F, p. 6647/8.
[32] "*The variation of light intensity over the area covered by the specimens and references must not exceed ± 10% of the mean*", BS 1006 (1990), Amendment 3 (1995), p. 1.
[33] "*White paint is often used for gallery walls as it contains titanium dioxide, which absorbs most of the UV radiation. Daylight reflected from a wall or ceiling painted with titanium white or zinc white paint only retains about one-tenth of its ultraviolet content, the other nine tenths being absorbed by the white paint. Thus, in a white painted room, areas illuminated only by reflected light are largely free from ultraviolet radiation*". Kühn (1986), p. 144.
[34] The summer months are more suitable for light ageing because most of the light during the winter period tends to be high in UV wavelengths, and the fading rate of the specimens can be very slow (Feller, 1994).
[35] "*Around room temperature, temperature changes have relatively little effect on fading. This is because the activation energy of the fading process is usually small, being in the range of only a few kcal/mole*". Brill (1980), p. 184.
[36] Representatives from the conservation science departments of The Tate Gallery, The British Museum, The National Gallery, The Victoria and Albert Museum all based in London, presented papers at the Accelerated Light Ageing in the UK, a conservation scientists meeting held at the Tate Gallery, London, 23rd February 2000. The papers described the use of fluorescent light to accelerate the ageing or bleaching of paper based materials.
[37] "*The tests have not been verified for evaluating the stability of color images produced with dry- and liquid-toner electrophotography, thermal dye transfer (also known as dye sublimation), ink jet, pigment-gelatine systems, offset lithography, gravure, and related color imaging systems.*" ANSI/NAPM IT9.9-1996, p. 1.
[38] ASTM D4303, Standard Test Method for Lightfastness of Pigments used in Artists' Paints also describes a test method for fluorescent light ageing which was used by Levison, Sutil and Vanderbrink (1987).
[39] Wilhelm *et al.* (1994), p. 81
[40] ANSI/NAPM IT9.9-1996
[41] Specifications obtained through email to Barbara Vogt, a research scholar at the IPI working on light fastness testing. IPI web address: www.rit.edu.
[42] Townsend (2000).
[43] Saunders *et al.* (1994, 1996).
[44] "*Standard single-phosphor Cool White fluorescent lamps are by far the most common type of fluorescent light and worldwide*". Wilhelm *et al.* (1994), p. 81
[45] As recommended by Daniels, McIntyre (1995) where polished stainless steel panels were employed in a fluorescent light ageing apparatus, so that light from the tubes is reflected from the panels, thus increasing the illumination on the base. P. 123-124. Also recommended by Wilhelm *et al.* (1994), p. 81.
[46] See reference 41.
[47] European museums often use 55-60% as better replicating the local climate. Erhardt and Mecklenburg (1994), p. 32.
[48] Originally, sodium bromide (NaBr) saturated salt solution was employed to control the relative humidity to around 58 %, but the solution was not easy to use as it is very tacky, and maintained humidity inside the fluorescent acrylic exposure box of approximately 50 %. 'Artsorb' is a material used for controlling humidity in enclosed spaces, and was also employed in the fluorescent exposure box but was not used with the light fastness test because the material could not be stabilized to the desired humidity with the equipment based at Camberwell College of Arts. The Artsorb kept increasing the humidity inside the exposure box to over 80 % RH.
[49] As recommended by Townsend. (2000).
[50] Saunders *et al.* (1996) used Thorn artificial daylight fluorescent lamps run for 100 hours before use in the fading chamber and were discarded after 3000 hours of operation to ensure that the spectral characteristics were reasonably consistent. Saunders *et al.* (1996), p. 88
[51] As recommended by Saunders *et al.* (1994), p.191, and Cannell (1983), p. 1983.
[52] BS 1006, A05 specifies that the samples should be visually examined until a fade equal to grey scale of 4 is reached. It was considered that visual examination of the samples was less accurate

than colour measurement using a Chroma meter because there was only on standard observer available for the testing (see reference 27). Therefore, ΔE_{ab} values were obtained using the ISO 105:A05 conversion equation for ΔE_{ab} to equivalent grey-scale rating. Smith (1997), p. 192.

[53] Non-woven polyester support fabric. Bondina Industrial Ltd., Greetland, Halifax, Yorkshire HX4 8NJ.

5.0 RESULTS

5.1 VISUAL EXAMINATION OF PRINT QUALITY UNDER AMBIENT LIGHT CONDITIONS

5.1.1 Iris print samples

The Iris samples were printed on two uncoated papers - Inveresk Somerset Velvet and Whatman Watercolour. Both sets of samples were produced with the same Iris 3047 printer using the same ink batch. The quality of the prints on both papers did not differ except that the photographic image was slightly stronger in colour on the Whatman paper, this being more obvious on the flesh tones areas. The colours reproduced were muted in tone compared to other the other ink jet printing inks tested, especially the magenta and black inks. The characteristic dot pattern of the ink jet printer was only slightly visible on the areas printed 5 % to 30 % particularly when yellow was mixed with the other ink colours. Line and type quality was good but wicking occurred and was visible under ambient light. For examples of these print samples see Appendix Q (pp. Q – 519 to Q – 520).

5.1.2 Lyson print samples

Lyson did not reproduce the print quality sample layout for the project. Therefore, a control sample was analysed. The prints were produced on the Mutoh Falcon RJ-800 Series printer (which had an Epson print engine), which was being used to test ink developed for use with the Epson Pro 9000, to be released by Epson later that year. Samples were printed on their own brand of coated ink jet papers for the fine art market (Soft Fine Art Watercolour paper and Rough Fine Art Watercolour paper), and the uncoated Whatman watercolour paper. Samples were produced using two different ink sets the Lysonic and Fotonic. The Fotonic ink set has a more bluish magenta than the Lysonic ink set, producing stronger reds and pinks. The yellow ink also appears to be slightly stronger and brighter.

There was a marked difference between the coated and uncoated papers. Both ink sets printed on the Whatman paper did not appear as vivid as on the coated papers, especially with the magenta and cyan inks and their mixtures. The two colour patches composed of the three ink colours cyan, magenta and yellow printed at 25 % and 50 % concentrations, had a red/brown hue on the coated papers but were more of a neutral grey on the uncoated papers. The ink jet dot pattern could be seen on some of the composite ink patches on all the papers and there was slight banding across some of the ink patches, but this was less obvious in the uncoated papers. The sample printed on the Lyson Rough Fine Art paper was quite easily damaged by surface abrasion. Printed line and type appeared slightly blurred under ambient light, even on the coated papers. Under magnification (X 10) sporadic dots could be seen to halo the lettering and lines. For examples of these print samples see Appendix Q (pp. Q – 521 to Q – 524).

5.1.3 Epson print samples

The Epson Pro 9000 samples were printed on three different ink jet printers, one printer was housed at the Camberwell College of Arts, one printer was situated at The Print Studio, London, and the other stationed at Epson (UK) Ltd, Hemel Hempstead. Samples were printed on two Epson coated papers Photo Glossy and Presentation Matt, two traditional uncoated papers Inveresk Somerset Velvet, Whatman Watercolour and a new artist paper treated with a coating for ink jet printers manufactured by Inveresk called Somerset Velvet Enhanced (ISVE). The new ISVE paper has the quality of a traditional fine art printmaking paper but contains an invisible coating which controls the ink jet droplet.

The samples printed on the Photo Glossy paper were comparable to photographic quality, although print resolution was visible to the naked eye at concentrations of 5 % to 50 %. There was also banding across the whole of the sample. All the colours printed were very vivid and the flesh tones on the image were faithfully reproduced. Line and type was reproduced well. Under magnification (X 10), the lines did not have a sharp edge but there were no satellite droplets of ink.

The Epson Presentation Matt paper printed at the London Print Studio also produced a good quality image with strong colours and good detail. The ink jet 'dithering pattern' was visible at print concentrations at 5 % to 50 %, but there was no banding. Line and type were of slightly better quality than the Photo Glossy paper. Samples printed on the uncoated papers on the printer housed at the Hemel Hempstead studio contained colours that were much more muted. Resolution was much less evident and could only be seen slightly on print concentrations of 5 % to 25 %. There was very little wicking of the ink on the line and type printing but fine lines of 0.1 point were not reproduced well. There was no visible difference between the two uncoated papers. The samples printed on the new Inveresk ink jet coated paper were much brighter and more vivid in colour, print resolution visibility was comparable to the Presentation Matt paper. Line and type was the same quality as the samples printed on the Epson coated papers.

The samples printed on the Epson Photo Stylus 870 printer, using Photo Glossy paper, were of exceptional quality and were comparable to the quality of a photograph. Colours were bright and vivid, and print resolution was not visible even on the lightly printed areas. Colours blended together seamlessly, flesh tones were accurate, and line and type were of good quality, except for graduated lines of 0.1 and 0.2 points which had a slightly pixelated appearance. For examples of these print samples see Appendix Q (pp. Q – 525 to Q – 530).

5.1.4 Hewlett Packard print samples

The Hewlett Packard samples were printed on Hewlett Packard Heavyweight coated paper. The first obvious characteristic of the print was the resolution, which could be clearly seen with the naked eye for print concentrations of 5 % to 75 %. Printed colours were bright and vivid but did not appear to have the same tonal range as the Epson Pro 9000 samples printed on the Epson Presentation Matt paper. Line and type were of good quality, but line reproduction of 0.1 points was not very clear, and the edges of the type did not appear sharp. Under magnification (X 10), satellite droplets could be seen haloing the lettering and lines. For examples of these print samples see Appendix Q (pp. Q – 531).

5.1.5 Canon print samples

Canon did not reproduce the print quality sample layout for the project. Therefore, the control sample was analysed. Overall, there was very little difference between the three printers tested – the Canon 1150 Colour Laser, the Canon CLC 900 and the Canon CLBP 460 PS. The only visible difference between the samples was that the magenta toner from the 1150 colour laser printer appeared to have a slight more bluish hue under ambient daylight. The composite 25 % and 50 % cyan, magenta and yellow and 25 % and 50 % cyan, magenta, yellow and black, had a brown tone on the 1150 colour laser and CLC 900 print samples, whereas the CLBP 460 PS printer produced the grey composites patches with a slight purple tone. Very faint banding lines could be seen on the patches of the CLBP 460 PS sample. Type was produced to a very good quality for all printers.

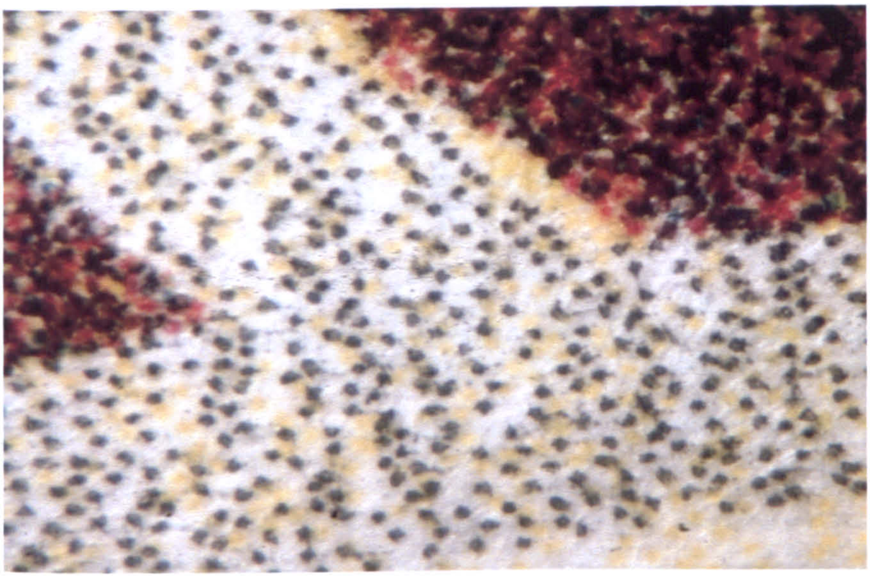

Fig. 5.1 Magnified photograph (X 10) of wicking that has occurred on an Iris print sample printed on Inveresk Somerset paper (1.1).

5.2 MICROSCAL LIGHT FASTNESS TESTER

5.2.1 Test conditions

Table 5.1 Lux levels at the cell perimeter of MB/U Light Fastness Tester recorded with a Lutron LX-101 lux meter.

Cell No.	*Lux Levels Before Testing (lux) of the nine cells (± 400 lux)*	*Lux Levels After Testing (lux) of the nine cells (± 400 lux)*
1	44,000	46,000
2	49,100	46,000
3	44,500	47,200
4	38,000	48,600
5	46,300	45,500
6	41,500	47,900
7	41,200	39,900
8	42,100	45,200
9	46,500	46,800
Average	43,689	45,900

The lux levels of the cells varied along the height of the exposure area by ± 400 lux. All measurements were taken from the middle of the cells.

Each cell was maintained at a temperature of 40 °C ± 1 °C throughout the duration of the tests. The black panel temperature ranged between 45 - 47 °C. Relative humidity could not be recorded as discussed in 4.4.3. The following cumulative lux-hours were calculated from the initial average readings taken from the above table: one week, 7,340 klux hours; two weeks 14,679 klux hours; three weeks 22,019 klux hours. After one week's exposure, sufficient fading had occurred in all print samples, except for the Hewlett Packard samples, which were exposed for two weeks, and the Canon samples which were exposed for three weeks.

5.2.2 Monitoring the variation of fading intensity of the Microscal lamp around the testing perimeter

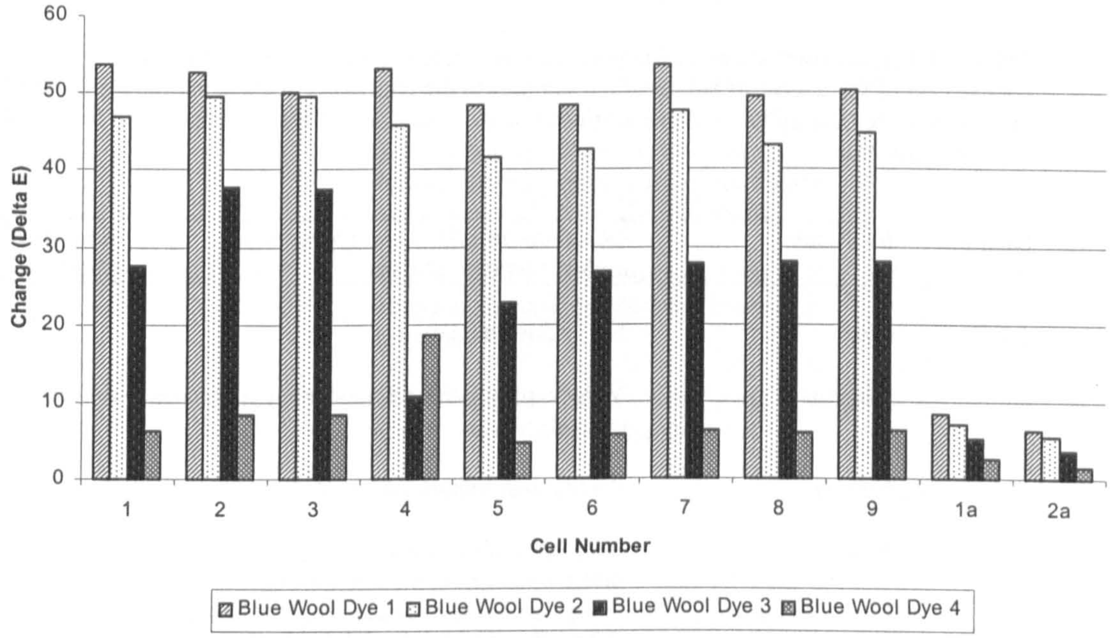

Fig. 5.2 Bar chart showing the change in ΔE_{ab} of blue wool scale dyes (one to four) after exposure in the Microscal MB/U light fastness tester for 7,340 klux hours in the nine cells positioned around the lamp perimeter. Each blue wool scale dye was light aged separately with different print sample sets. The change in ΔE_{ab} of the first two blue wool scales (Bars 1a and 2a, positioned in cells 1 and 2) exposed with the first two sets of samples had much lower fading results than the subsequent test samples. It was realised that, although the lamp was left for a period of 100 hours before testing to allow for the spectral characteristics of the lamp to achieve a consistent level, the lamp needed to be left on for a further two weeks before testing commenced. These sets of samples were light aged again.

5.2.3 Results of the Iris print samples after light ageing in the Microscal Light Fastness Tester for one week or 7,340 klux hours

Table 5.2 Visual observations of Iris print samples under ambient light conditions, and comparison of the degree of fading of the samples to the Blue wool scale using the BS 1006 (A02) grey scale under D_{50} lighting. The Iris print samples were exposed to Microscal lamp for one week or 7,340 klux hours.

Sample No.	*Ink Patch*	*Observations after light ageing under ambient light conditions*	*Blue Wool Scale Rating (1-7)*
1.1	Cyan	No visible change	7
	Magenta	Very slightly lighter in tone compared to the control.	6-7
	Yellow	Patch much lighter than control.	3
	Black	Ink patch faded rapidly on exposure, and under went colour change turning to a pale orange colour (see 5.3.2). Slightly less fading than black ink on 1.1 sample	2
	Red	Very slightly lighter in tone compared to the control.	6
	Green	Lighter in tone compared to the control, patch becoming more cyan in tone.	5
	Blue	Very slightly lighter in tone compared to the control.	6
	100 % C 50 % K	Black ink faded only, patch becomes cyan in tone.	5
	100 % M 50 % K	Black ink faded only, patch become magenta in tone.	4
	100 % Y 50 % K	Showed rapid fading on exposure to light, fading to a pale yellow colour.	1
	25/50/75 % Cyan	No visible change on 75 % ink concentration. 50 % and 25 % patches show slight yellow hue.	7
	25/50/75 % Magenta	50 % and 25 % patches showed slight fading, changing to a paler tone of magenta.	6 (75 % - 7)

Table 5.2 Continued

Sample No.	*Ink Patch*	*Observations after light ageing under ambient light conditions*	*Blue Wool Scale Rating (1-7)*
	25/50/75 % Yellow	Showed rapid fading on exposure to light, fading to a paler tone. No colour left on 25 % ink patch.	2
	25/50/75 % Black	Showed rapid fading on exposure to light, and patches under went colour change turning to a very pale orange tone. Hardly any colour visible on 25% ink patch.	1
	25/50 % CMY	The ink patches both showed similar fading contrast, and changed colour turning to a grey/purple hue.	4
	25/50 % CMYK	The ink patches both showed similar fading contrast, changing to a lighter tone.	3
	Paper	Paper slightly whiter.	N/A
1.2	Cyan	No visible change	7
	Magenta	Very slightly lighter in tone compared to the control.	7
	Yellow	Patch much lighter than control.	4
	Black	Ink patch faded rapidly on exposure, and under went colour change turning to a pale orange colour (see 5.3.2).	1
	Red	Very slightly lighter in tone compared to the control.	6
	Green	Lighter in tone compared to the control, patch becoming more cyan in tone.	5
	Blue	Very slightly lighter in tone compared to the control.	6
	100 % C 50 % K	Black ink faded only, patch becomes cyan in tone.	5
	100 % M 50 % K	Black ink faded only, patch becomes magenta in tone.	4
	100 % Y 50 % K	Showed rapid fading on exposure to light, fading to a pale yellow colour.	1

Table 5.2 Continued

Sample No.	*Ink Patch*	*Observations after light ageing under ambient light conditions*	*Blue Wool Scale Rating (1-7)*
	25/50 /75 % Cyan	No visible change on 75 % ink concentration. 50 % and 25 % patches show slight yellow hue.	7
	25/50/75 % Magenta	50 % and 25 % patches showed slight fading, changing to a paler tone of magenta.	6 (75 % - 7)
	25/50 /75 % Yellow	Showed rapid fading on exposure to light, fading to a paler tone. No colour left on 25 % ink patch	2
	25/50 /75 % Black	Showed rapid fading on exposure to light, and patches under went colour change turning to a very pale orange tone. Hardly any colour visible on 25% ink patch.	1
	25/50 % CMY	The ink patches both showed similar fading contrast, and changed colour turning to a grey/purple hue.	4
	25/50 % CMYK	The ink patches both showed similar fading contrast, changing to a lighter tone.	3
	Paper	Paper slightly whiter.	N/A

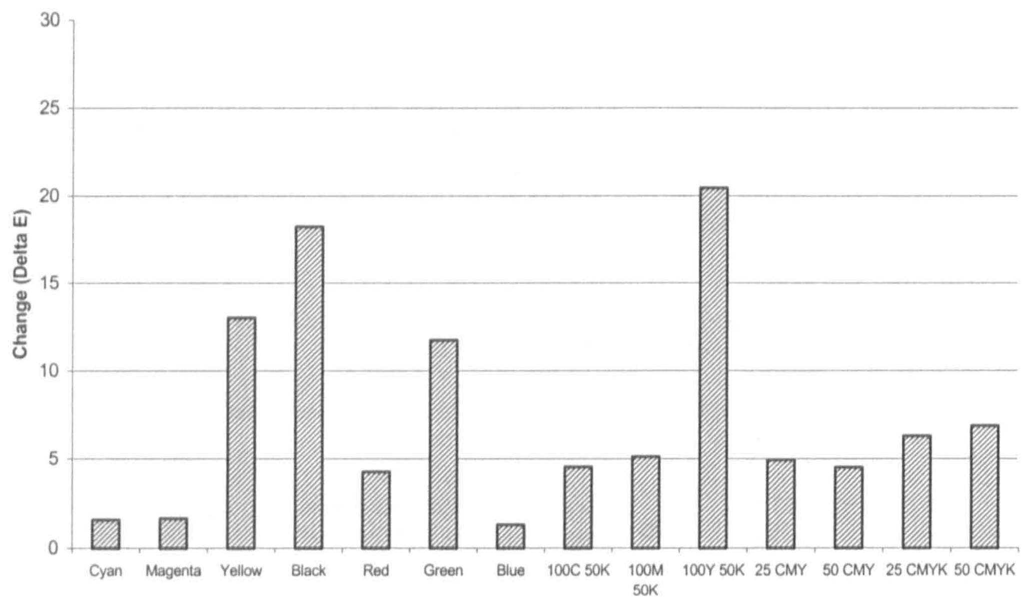

Fig 5.3 Bar chart showing the change in ΔE_{ab} of the primary ink patches and their colour combinations for the Iris Morgan FA ink set printed on Somerset paper (1.1).

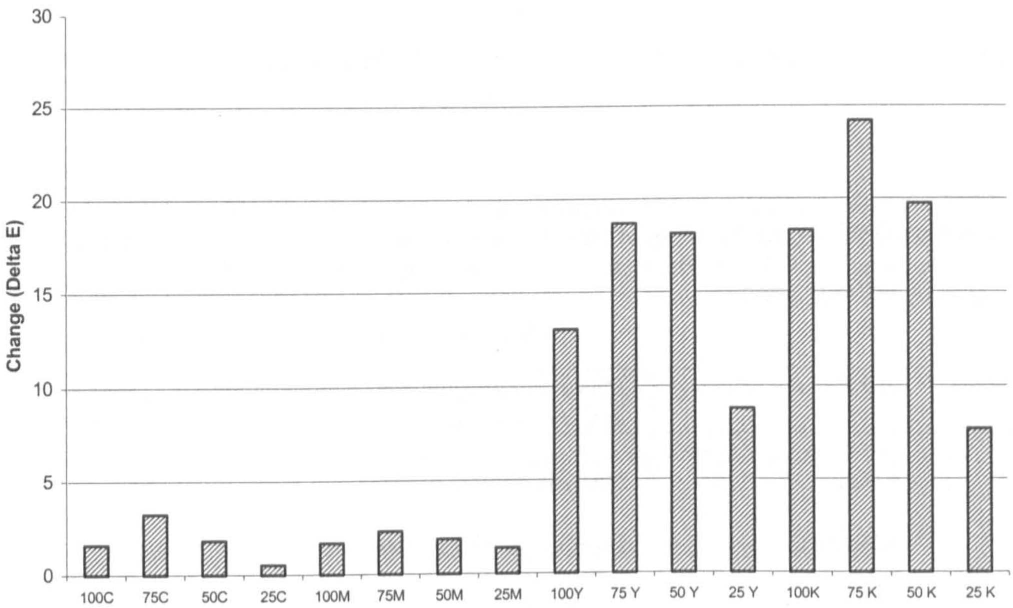

Fig. 5.4 Bar chart showing the change in ΔE_{ab} of the primary ink patches printed at four different concentrations for the Iris Morgan FA ink set printed on Somerset paper (1.1).

5.2.4 Results of the Lyson print samples after light ageing in the Microscal Light Fastness Tester for two weeks or 14,679 klux hours

Table 5.3 Visual observations of Lyson print samples under ambient light conditions, and comparison of the degree of fading of the samples to the blue wool scale using the BS 1006 (A02) grey scale under D_{50} lighting. The Lyson print samples were exposed to Microscal lamp for one week or 14,679 klux hours.

Sample No.	*Ink Patch*	*Observations after light ageing under ambient light conditions*	*Blue Wool Scale Rating (1-7)*
2.1	Cyan	No visible change.	6
	Magenta	Patch faded to a lighter tone.	3
	Yellow	Patch faded to a lighter tone.	3
	Black	Patch faded to a lighter tone, with a slight colour change with an orange hue.	6
	Red	Very slightly lighter in tone compared to the control.	4
	Green	Lighter in tone compared to the control, patch becoming more cyan in tone.	3
	Blue	Very slightly lighter in tone compared to the control.	5
	100 % C 50 % K	No visible colour change.	6
	100 % M 50 % K	Patch faded to a lighter tone.	6
	100 % Y 50 % K	Patch faded to a lighter tone.	6
	25/50/75 % Cyan	No visible change on 75 % ink concentration. Slight fading on the 50 % and 25 %, and patches had a slight yellow hue.	6
	25/50/75 % Magenta	Showed rapid fading on exposure to light, fading to a paler tone.	3
	25/50/75 % Yellow	Showed rapid fading on exposure to light, fading to a paler tone.	2
	25/50/75 % Black	Patches faded to a light tone, and had a slight orange hue.	6
	25/50 % CMY	Similar fading rates for both ink patches, changed colour turning from grey to pale purple tone.	3

Table 5.3 Continued

Sample No.	*Ink Patch*	*Observations after light ageing under ambient light conditions*	*Blue Wool Scale Rating (1-7)*
	25/50 % CMYK	Similar fading rates for both ink patches, changing to a much lighter tone.	4
	Paper	Coated paper appears very slightly whiter than control.	N/A
2.2	Cyan	Very slight fading.	6
	Magenta	Faded unevenly, changing to a paler tone.	3
	Yellow	Patch turned darker on exposure to light, with colour deepening.	5 (Deeper)
	Black	Visible fading, patch-changed colour fading to a pale orange.	2
	Red	Patch faded to a lighter red, becoming more yellow in tone.	4
	Green	Patch faded to a lighter green, becoming more cyan in tone.	4
	Blue	Patch faded to a lighter tone.	4
	100 % C 50 % K	Black ink faded only, patch becomes cyan in tone.	3
	100 % M 50 % K	Patch showed rapid fading on exposure to light, fading to a pale magenta colour.	2
	100 % Y 50 % K	Patch showed rapid fading on exposure to light, fading to pale yellow colour.	2
	25/50/75 % Cyan	No visible change on 75 % ink concentration. 50 % and 25 % patches show slight yellow hue.	5 (75 % - 6)
	25/50/75 % Magenta	Patches faded rapidly on exposure to light. Very slight colour left on 50 % and 25 % patches.	1 (75 % - 2)
	25/50/75 % Yellow	Showed rapid fading on exposure to light, fading to a paler tone. No colour left on 25 % ink patch	2
	25/50/75 % Black	Showed rapid fading on exposure to light, and patches under went colour change turning to a very pale orange tone. Hardly any colour visible on 50 % and 25 % ink patch.	1

Table 5.3 Continued

Sample No.	*Ink Patch*	*Observations after light ageing under ambient light conditions*	*Blue Wool Scale Rating (1-7)*
	25/50 % CMY	Similar fading rates for both ink patches. Changed colour turning from grey to pale blue tone.	2
	25/50 % CMYK	Similar fading rates for both ink patches, changing to a much lighter tone.	2
	Paper	Coated paper appears very slightly whiter than control.	N/A
2.3		**Sample set void, due to over heating during test exposure.**	
2.4	Cyan	Very slight fading.	6
	Magenta	Patch faded to a paler tone.	3
	Yellow	Patch turned darker on exposure to light, with colour deepening.	5 (Darker)
	Black	Visible fading, patch-changed colour fading to an orange/grey.	3
	Red	Patch faded to a much lighter red, becoming more yellow in tone.	2
	Green	Patch faded to a lighter green, becoming slightly cyan in tone.	4
	Blue	Patch faded to a much lighter tone.	2
	100 % C 50 % K	Black ink faded only, patch becomes cyan in tone.	3
	100 % M 50 % K	Showed rapid fading on exposure to light, fading to a pale magenta colour.	2
	100 % Y 50 % K	Showed rapid fading on exposure to light, fading to a yellow/green colour.	2
	25/50/75 % Cyan	No visible change on 75 % ink concentration. 50 % and 25 % patches show slight yellow cast.	6
	25/50/75 % Magenta	Patches faded to a lighter tone.	2
	25/50/75 % Yellow	75 % ink patch colour had darkened. On 50 % and 25 % ink patches yellow had faded slightly.	75 % - 5 (Darker), 25/50 % - 4

Table 5.3 Continued

Sample No.	*Ink Patch*	*Observations after light ageing under ambient light conditions*	*Blue Wool Scale Rating (1-7)*
	25/50/75 % Black	Showed rapid fading on exposure to light, and patches under went colour change turning to a very pale orange tone.	2
	25/50 % CMY	Similar fading rates for both ink patches, changing to a lighter tone of grey.	3
	25/50 % CMYK	Similar fading rates for both ink patches, changing to a much lighter grey with a slightly brown tone.	3
	Paper	Coated paper appears very slightly whiter than control.	N/A

Overall, there was a marked difference in fading from the Lysonic ink set compared to the Fotonic ink set, with the former ink performing better than the latter. There was also a noticeable difference between the coated and uncoated papers for the Fotonic ink set, with the colour patches printed on the Lyson Rough Fine Art paper having better light fastness results, than when printed on the uncoated Whatman paper.

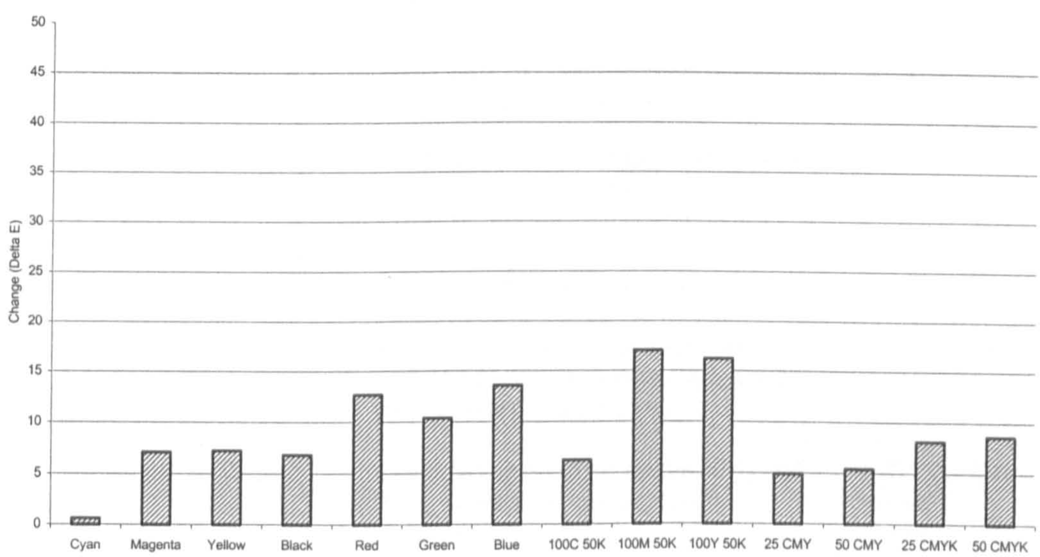

Fig. 5.5 Bar chart showing the change in ΔE_{ab} of the primary ink patches and their colour combinations for the Fotonic ink set printed on Whatman watercolour paper (2.4) after 14,679 klux hours exposure in the Microscal Tester.

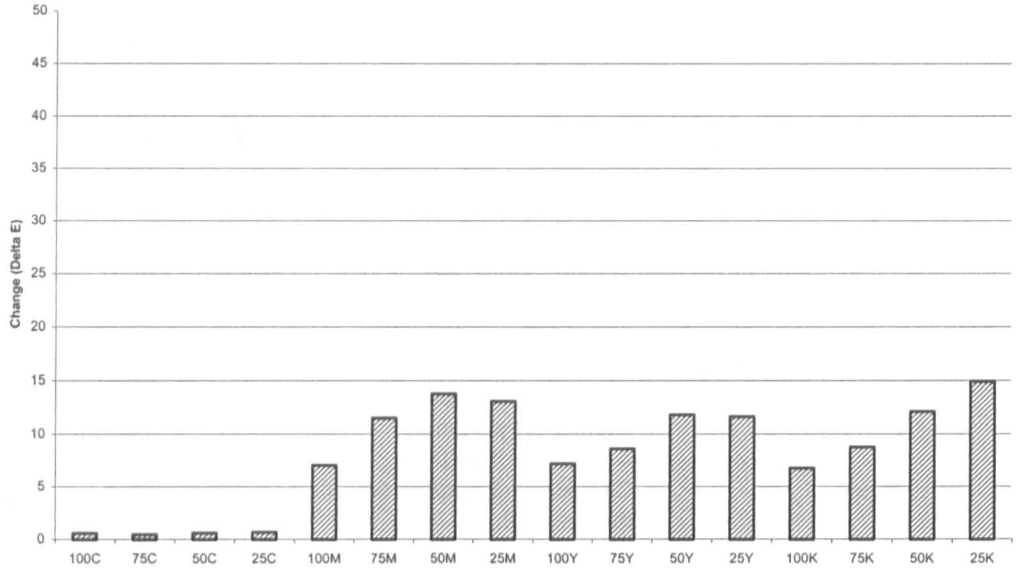

Fig. 5.6 Bar chart showing the change in ΔE_{ab} of the primary ink patches printed at four different concentrations for the Fotonic ink set printed on Whatman watercolour paper (2.4) after 14,679 klux hours exposure in the Microscal Tester.

5.2.5 Results of the Epson print samples after light ageing in the Microscal Light Fastness Tester for one week or 7,340 klux hours

Table 5.4 Visual observations of Epson print samples under ambient light conditions, and comparison of the degree of fading of the samples to the blue wool scale using the BS 1006 (A02) grey scale under D_{50} lighting. The Epson print samples were exposed to Microscal lamp for one week or 7,340 klux hours.

Sample No.	*Ink Patch*	*Observations after light ageing under ambient light conditions*	*Blue Wool Scale Rating (1-7)*
3.1	Cyan	Patch faded to a lighter tone.	4
	Magenta	Patch faded rapidly on exposure to light, fading to pale magenta tone.	3
	Yellow	No visible change.	7 or greater
	Black	Patch faded, and changed colour turning to an orange tone.	5
	Red	Patch faded to a lighter red, becoming more yellow in tone.	2
	Green	Patch faded to a slightly lighter tone.	5
	Blue	Sample damaged by potassium carbonate saturated salt solution.	Void
	100 % C 50 % K	Black ink faded only, patch becomes cyan in tone.	3 - 4
	100 % M 50 % K	Patch showed rapid fading on exposure to light, fading to a paler tone.	3
	100 % Y 50 % K	Patch showed rapid fading on exposure to light, fading to a paler tone. Patch faded to a pale yellow/green colour.	3
	25/50/75 % Cyan	Patches faded to a lighter tone.	3
	25/50/75 % Magenta	Patches faded rapidly on exposure to light. 50 % and 25 % ink concentration patches faded to a pale grey.	1 (75 % - 2)
	25/50/75 % Yellow	Slight fading occurred on the 50 % and 25 % patches. 75 % was visibly unchanged.	6 (75 % - 7 or greater)
	25/50/75 % Black	All patches faded to a pale green colour.	3

Table 5.4 Continued

Sample No.	*Ink Patch*	*Observations after light ageing under ambient light conditions*	*Blue Wool Scale Rating (1-7)*
	25/50 % CMY	All patches faded to a pale green colour.	2
	25/50 % CMYK	25 % patch faded to a pale green colour. 50 % patch faded and change colour turning dark green.	2
	Paper	Coated paper is very slightly whiter than control.	N/A
3.2	Cyan	Patch faded to a lighter tone.	3
	Magenta	Patch faded rapidly on exposure to light, fading unevenly to a much paler magenta tone.	1
	Yellow	Patch faded slightly to a paler tone.	6
	Black	Patch faded, and changed colour turning to an orange tone.	2
	Red	Patch faded to a lighter red, becoming an orange/yellow tone.	2
	Green	Patch faded to a slightly lighter tone.	5
	Blue	Patch faded to a lighter blue tone.	3
	100 % C 50 % K	Black ink faded only, patch becomes bluer in tone.	3
	100 % M 50 % K	Patch showed rapid fading on exposure to light, fading to a much paler tone, and fading colour was uneven.	2
	100 % Y 50 % K	Patch showed rapid fading on exposure to light, fading to a pale yellow colour.	1
	25/50/75 % Cyan	Patches faded to a lighter tone.	3
	25/50/75 % Magenta	Patches faded rapidly on exposure to light. All the colours faded from the exposed areas.	1
	25/50/75 % Yellow	No visible colour change.	7 or greater
	25/50/75 % Black	Patches faded to a pale orange colour.	1
	25/50 % CMY	All patches faded to a pale green colour.	1
	25/50 % CMYK	All patches faded to a pale green colour.	1
	Paper	No change visible.	N/A

Table 5.4 Continued

Sample No.	*Ink Patch*	*Observations after light ageing under ambient light conditions*	*Blue Wool Scale Rating (1-7)*
3.3	Cyan	Patch faded to a lighter tone.	3
	Magenta	Patch faded rapidly on exposure to light, fading to a much paler magenta tone.	1
	Yellow	Patch faded rapidly on exposure to light, fading to a much paler yellow tone.	2
	Black	Patch faded to a much paler tone, and changed colour turning to an orange hue.	3
	Red	Patch faded to a lighter red.	1
	Green	Patch faded to a slightly lighter tone.	3
	Blue	Patch faded to a lighter blue tone.	3
	Paper	Paper is slightly whiter than control.	N/A
		Other colour patches were not available for testing.	
3.4	Cyan	Patch faded to a lighter tone.	3
	Magenta	Patch faded rapidly on exposure to light, fading to a much paler magenta tone.	1
	Yellow	Patch faded rapidly on exposure to light, fading to a much paler yellow tone.	2
	Black	Patch faded to a much paler tone, and changed colour turning to an orange hue.	3
	Red	Patch faded to a lighter red.	1
	Green	Patch faded to a slightly lighter tone.	3
	Blue	Patch faded to a lighter blue tone.	3
	Paper	Paper is slightly whiter than control.	N/A
		Other colour patches were not available for testing.	
3.5	Cyan	Patch faded to a slightly lighter tone.	4
	Magenta	Patch faded to pale magenta tone.	3
	Yellow	Slight fading has occurred.	5
	Black	Patch faded, and changed colour turning to an orange tone.	3

Table 5.4 Continued

Sample No.	*Ink Patch*	*Observations after light ageing under ambient light conditions*	*Blue Wool Scale Rating (1-7)*
	Red	Patch faded to a lighter red, becoming more yellow in tone.	2
	Green	Patch faded to a slightly lighter tone.	5
	Blue	Patch faded to a lighter tone.	4
	100 % C 50 % K	Black ink faded only, patch becomes cyan in tone.	4
	100 % M 50 % K	Patch showed rapid fading on exposure to light, fading to a paler tone.	2
	100 % Y 50 % K	Patch showed rapid fading on exposure to light, fading to a paler tone.	1
	25/50/75 % Cyan	Patches faded to a lighter tone. 50 % and 25 % patches also have a slightly yellow hue, which appears to have been caused by the yellowing of the paper underneath.	4
	25/50/75 % Magenta	Patches faded rapidly on exposure to light.	1
	25/50/75 % Yellow	Slight fading occurred on the 50 % and 25 % patches. 75 % was visibly unchanged.	5
	25/50/75 % Black	All patches faded to a pale orange colour.	1
	25/50 % CMY	All patches faded to a pale green colour.	1
	25/50 % CMYK	All patches faded to a pale green colour.	2
	Paper	Coated paper slightly yellowed on exposure to light.	N/A
3.6	Cyan	Patch faded to a slightly lighter tone.	4
	Magenta	Patch faded rapidly on exposure to light, fading unevenly to a much paler magenta/orange tone.	2
	Yellow	No visible change.	7 or greater
	Black	Patch faded to a slightly paler tone. Patch has a slight orange hue.	7 or greater
	Red	Patch faded to a lighter red, becoming more yellow in tone.	2
	Green	Patch faded to a lighter tone.	4
	Blue	Patch faded to a much lighter tone.	3

Table 5.4 Continued

Sample No.	*Ink Patch*	*Observations after light ageing under ambient light conditions*	*Blue Wool Scale Rating (1-7)*
	100 % C 50 % K	Patch faded to a lighter tone.	4
	100 % M 50 % K	Patch showed rapid fading on exposure to light, fading to a much paler tone.	2
	100 % Y 50 % K	Patch faded to a lighter tone.	3
	25/50/75 % Cyan	Patches faded to a lighter tone.	4
	25/50/75 % Magenta	Patches faded to a light tone of magenta. 75 % patch has a slight orange hue.	3
	25/50/75 % Yellow	Slight fading occurred on the 50 % and 25 % patches. 75 % was visibly unchanged.	6 (50 % - 5)
	25/50/75 % Black	50 % and 25 % patches faded to a lighter tone of grey, but patches have an orange hue. 75 % patch has faded becoming slightly green/grey in colour.	3
	25/50 % CMY	All patches faded to a pale brown/grey colour.	3
	25/50 % CMYK	25 % patch faded to a pale grey/brown colour. 50 % patch faded to a green/brown colour.	3
	Paper	Coated paper yellowed very slightly on exposure to light.	N/A

The sample set printed on the Epson Photo Glossy paper performed overall better than the Epson Presentation Matt paper. The magenta and black inks faded more rapidly on the Somerset Velvet Enhanced compared to the other papers tested. Both the uncoated Somerset Velvet and Whatman papers showed larger ΔE_{ab} values for the CMYK colour patches tested, compared to the Epson coated papers.

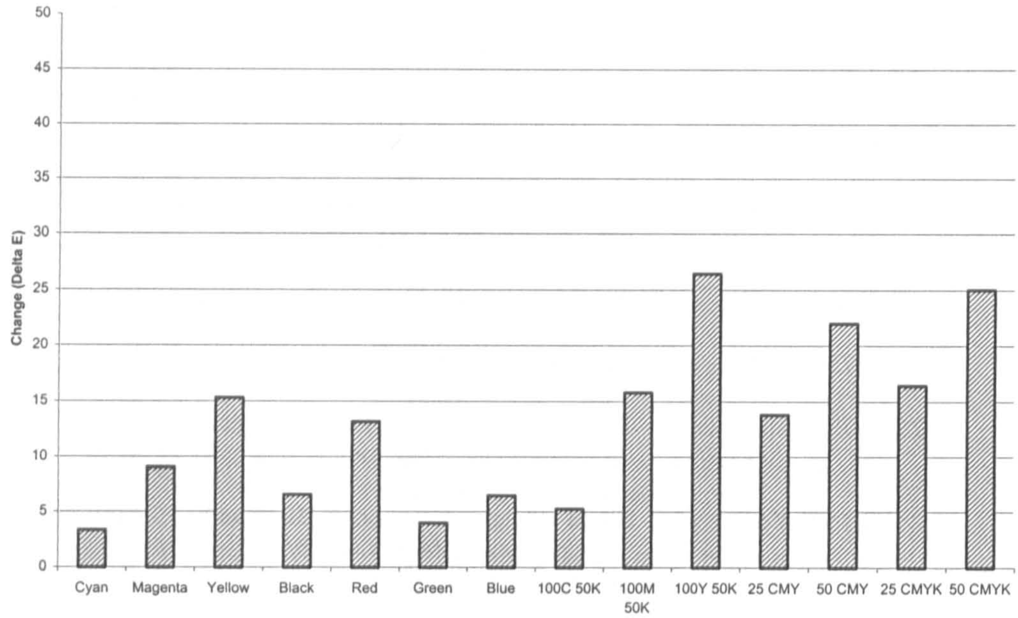

Fig. 5.7 Bar chart showing the change in ΔE_{ab} of the primary ink patches and their colour combinations for the Epson Pro 9000 ink set printed on the Epson Presentation Matt paper (3.5) at different ink combinations after 7,340 klux hours exposure in the Microscal Tester.

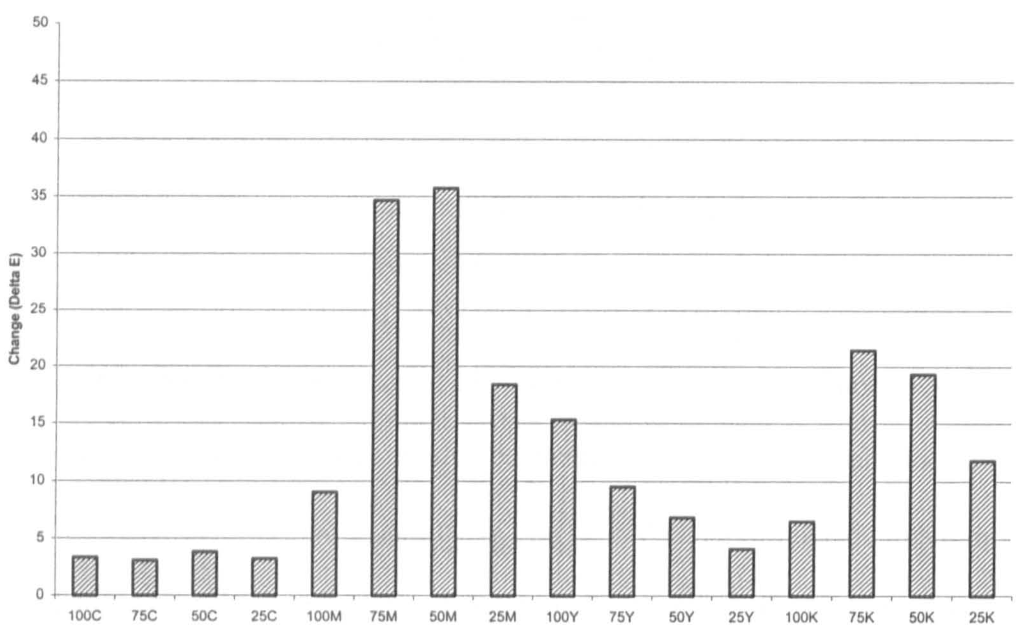

Fig. 5.8 Bar chart showing the change in ΔE_{ab} of the primary ink patches printed at four different concentrations for the Epson Presentation Matt paper (3.5) at different ink concentrations after 7,340 klux hours in the Microscal Tester.

5.2.6 Results of the Hewlett Packard print samples after light ageing in the Microscal Light Fastness Tester for one week or 14,679 klux hours

Table 5.5 Visual observations of Hewlett Packard print samples under ambient light conditions, and comparison of the degree of fading of the samples to the blue wool scale using the BS 1006 (A02) grey scale under D_{50} lighting. The Hewlett Packard print samples were exposed to Microscal lamp for one week or 14,679 klux hours.

Sample No.	*Ink Patch*	*Observations after light ageing under ambient light conditions*	*Blue Wool Scale Rating (1-7)*
4.1	Cyan	Patch faded to a lighter tone.	3
	Magenta	Patch faded to a lighter colour, with a slight orange tone.	2
	Yellow	Slight fading has occurred on this patch. The yellow ink patch also contains very small droplets of cyan and magenta ink. The cyan and magenta inks have faded causing the colour change.	5
	Black	Patch faded to a lighter tone.	3
	Red	Patch faded to a lighter colour, turning yellow in tone.	5
	Green	Patch faded to a lighter tone.	4
	Blue	Patch faded to a lighter tone.	4
	100 % C 50 % K	Patch faded to a lighter tone.	4/5
	100 % M 50 % K	Patch faded to a lighter tone.	4
	100 % Y 50 % K	Patch faded to a lighter tone.	3
	25/50/75 % Cyan	All patches showed some degree of fading.	5
	25/50/75 % Magenta	All patches showed some degree of fading.	5
	25/50/75 % Yellow	All patches showed slight degree of fading. Yellow ink patch also contains very small droplets of cyan and magenta ink. The cyan and magenta inks have faded, causing the colour changes.	5
	25/50/75 % Black	All patches have faded and change colour fading to a green tone.	4

Table 5.5 Continued

Sample No.	*Ink Patch*	*Observations after light ageing under ambient light conditions*	*Blue Wool Scale Rating (1-7)*
	25/50 % CMY	Similar fading rates for both ink patches, changed colour turning from grey to pale green tone.	4
	25/50 % CMYK	Similar fading rates for both ink patches, changed colour turning from grey to pale green tone.	3
	Paper	Coated paper has yellowed very slightly.	N/A

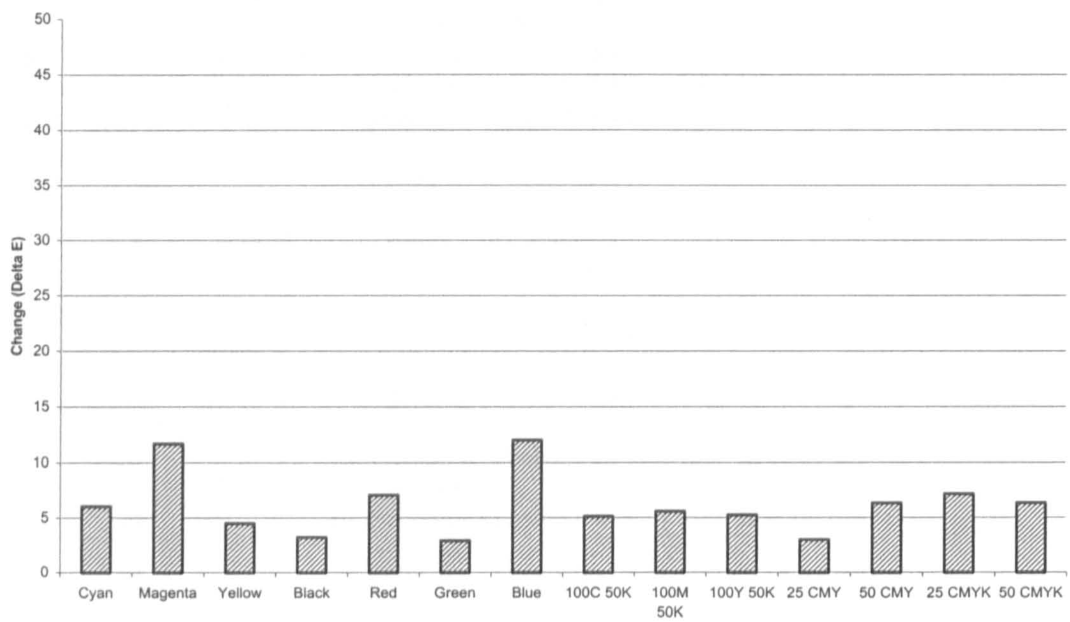

Fig. 5.9 Bar chart showing the change in ΔE_{ab} of the primary ink patches and their colour combinations for the Hewlett Packard ink set printed on Hewlett Packard Heavy Weight coated paper (4.1) after 14,679 klux hour exposure in the Microscal Tester.

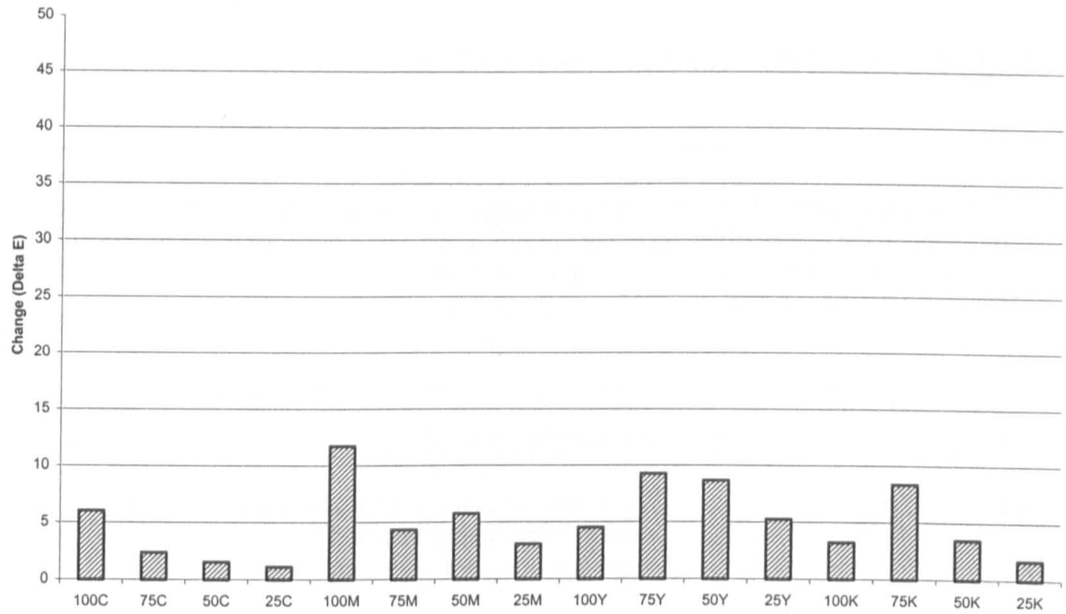

Fig. 5.10 Bar chart showing the change in ΔE_{ab} of the primary ink patches printed at four different concentrations for the Hewlett Packard ink set printed on Hewlett Packard Heavy Weight coated paper (4.1) after 14,679 klux hour exposure in the Microscal Tester.

5.2.7 Results of the Canon print samples after light ageing in the Microscal Light Fastness Tester for three weeks or 22,019 klux hours

Table 5.6 Visual observations of Canon print samples under ambient light conditions, and comparison of the degree of fading of the samples to the blue wool scale using the BS 1006 (A02) grey scale under D_{50} lighting. The Canon print samples were exposed to Microscal lamp for three weeks or 22,019 klux hours.

Sample No.	*Ink Patch*	*Observations after light ageing under ambient light conditions*	*Blue Wool Scale Rating (1-7)*
5.1	Cyan	Toner has not faded, but the paper support underneath has yellowed, and has given the toner a noticeable yellow tone.	6
	Magenta	Toner faded slightly, but the paper support underneath has yellowed, and has given the toner a noticeable yellow tone.	6
	Yellow	Toner faded rapidly on exposure, fading to a pale yellow.	2
	Black	No visible change.	7 or greater
	Red	The yellow toner has faded, and the patch has changed colour, turning to magenta.	5
	Green	The yellow toner has faded, and the patch has changed colour, turning to cyan.	3
	Blue	No visible change.	7 or greater
	100 % C 50 % K	Patch faded to a lighter tone.	6
	100 % M 50 % K	Patch faded to a slightly lighter tone.	6
	100 % Y 50 % K	Patch faded to a lighter tone.	4
	25/50/75 % Cyan	Toner has faded slightly, but the paper support underneath has yellowed, and has given the toner a noticeable yellow tone.	7 (75 % - greater than 7)
	25/50/75 % Magenta	Toner faded slightly, but the paper support underneath has yellowed, and has given the toner a noticeable yellow tone.	7 or greater
	25/50/75 % Yellow	Toner faded rapidly on exposure, fading to a pale yellow.	1

Table 5.6 Continued

Sample No.	*Ink Patch*	*Observations after light ageing under ambient light conditions*	*Blue Wool Scale Rating (1-7)*
	25/50/75 % Black	Toner faded, but the paper support underneath has yellowed and has given the toner a noticeable yellow tone.	6
	25/50 % CMY	Similar fading rates for both toner patches. Patches changed colour turning from grey to purple tone.	4
	25/50 % CMYK	Similar fading rates for both toner patches. Patches changed colour turning from grey to purple tone.	5
	Paper	Paper yellowed noticeably.	N/A
5.3	Cyan	Toner has faded slightly. The paper support underneath has yellowed, and has given the toner a noticeable yellow hue.	6
	Magenta	Toner faded slightly, but the paper support underneath has yellowed, and has given the toner a noticeable yellow hue.	4
	Yellow	Toner faded to a pale yellow.	4
	Black	Toner has not faded, but the paper support underneath has yellowed, and has given the patch a slight yellow tone.	7 or greater
	Red	Patch has faded, turning to a lighter tone of red.	6
	Green	Patch has faded, turning to a lighter tone of green. Patch has a slight cyan tone.	5
	Blue	Slightly faded to a lighter blue colour.	6
	100 % C 50 % K	Toner has faded slightly. The paper support underneath has yellowed, and has given the toner a noticeable yellow hue.	7 or greater
	100 % M 50 % K	Patch faded to a slightly lighter tone.	4
	100 % Y 50 % K	Patch faded to a lighter tone.	5
	25/50/75 % Cyan	Toner has faded. The paper support underneath has yellowed, and has given the toner a noticeable yellow hue.	5 (75 % - 6)
	25/50/75 % Magenta	Toner faded, but the paper support underneath has yellowed, and has given the toner a noticeable yellow hue.	3
	25/50/75 % Yellow	Toner faded to a pale yellow.	2

Table 5.6 Continued

Sample No.	*Ink Patch*	*Observations after light ageing under ambient light conditions*	*Blue Wool Scale Rating (1-7)*
	25/50/75 % Black	Toner has faded, and the paper support underneath has yellowed, and has given the patch a slight yellow tone.	6 (75 % - 7 or greater)
	25/50 % CMY	Similar fading rates for both toner patches. Patches changed colour turning from grey to purple tone.	4
	25/50 % CMYK	Similar fading rates for both toner patches, fading to a lighter tone.	5
	Paper	Paper yellowed noticeably.	N/A
		5.2, 5.4 and 5.5 samples sets were not light aged with the Microscal Light Fastness Tester, because there were not enough samples available.	

The Canon Ultra White paper had yellowed on exposure to the light test. This discolouration altered the appearance of many of the toners, especially where they were printed at lower toner concentrations.

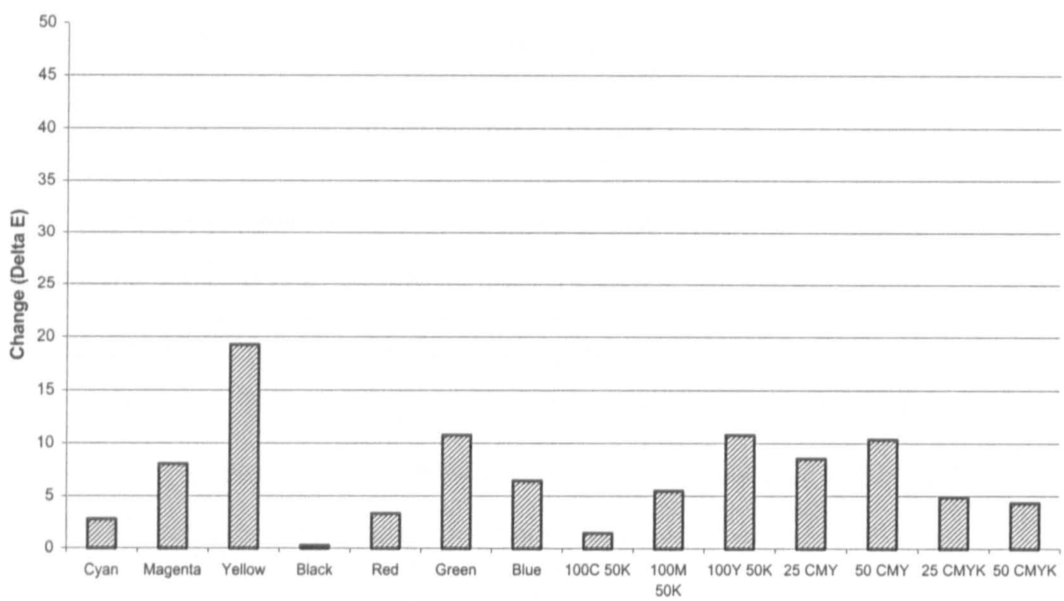

Fig. 5.11 Bar chart showing the change in ΔE_{ab} of the primary ink patches and their different colour combinations for the Canon CLC 900 toner printed on Ultra White paper (5.3), after 22,019 klux hour exposure in the Microscal Tester.

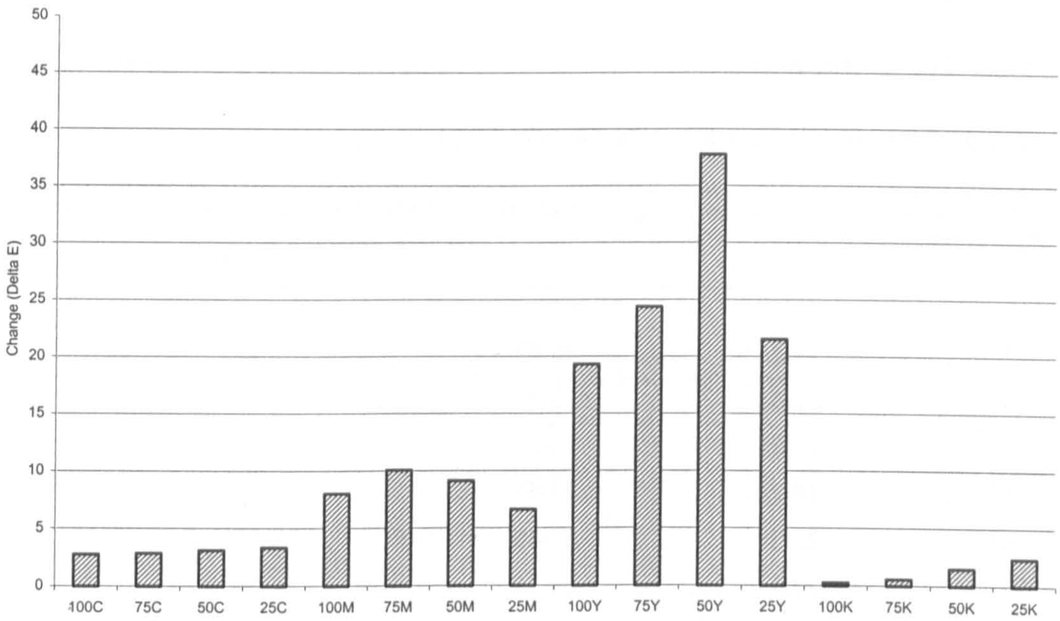

Fig. 5.12 Bar chart showing the change in ΔE_{ab} of the primary ink patches printed at four different concentrations for the Canon CLC 900 toner printed on Ultra White paper (5.3), after 22,019 klux hour exposure to the Microscal Tester.

5.3 NATURAL DAYLIGHT LIGHT FAST TESTING

5.3.1 Test conditions

Table 5.7 Recorded test conditions for the natural daylight exposure.

Week No.	*Temperature (°C)*	*Relative Humidity (%)*	*Cumulative Lux Hours (klux hours)*
1	-	-	-
2	19-24.5	36-49	413
3	21-32	35-47	2,138
4	19-25	39-50	9,569
5	18-24.5	31-50	11,253
6	23-29	31-45	17,540
7	22.5-31	31-50	20,667
8	22.5-34.5	25-50	23,546
9	23-32	32-47	26,627
10	21-27	35.5-40.5	27,994
11	23-28.5	38.5-50	29,728
12	22-25.5	40.5-55	31,248
13	23-28	37-50	33,002
14	23-32.5	36-45	35,897
15	23.5-28.5	43.5-52	37,847
16	24.5-26.5	44.5-53.5	39,444
17	24.5-30.5	40.5-53	41,781
18	22-30	38-50	43,905
19	20-28	40-52.5	46,620
20	20.5-29	38-50	48,925
21	19-27	36-49	50,863

Testing started on the 26th April 2000 and finished on the 20th September 2000. The black panel temperature ranged from 0 °C on cloudy days to + 6 °C above the ambient temperature on bright sunny days. The coated matt papers and the ISVE paper had the highest black panel temperatures.

5.3.2 Results of the Iris print samples after light ageing in natural daylight for approximately 50,863 klux hours

Table 5.8 Visual observations of Iris print samples under ambient light conditions, and comparison of the degree of fading of the samples to the blue wool Scale using the BS 1006 (A02) grey scale under D_{50} lighting.

Sample No.	*Ink Patch*	*Observations after light ageing under ambient light conditions*	*Blue Wool Scale Rating (1-7)*
1.1 (uncovered)	Cyan	No visible change.	7 or greater
	Magenta	No visible change.	7 or greater
	Yellow	Patch rapidly faded on exposure to light, fading to a lighter tone.	3
	Black	Ink patch faded rapidly on exposure and underwent colour change turning to a pale orange colour (see fig. 5.13).	2
	Paper	Paper slightly yellowed.	N/A
1.1 (covered with a UV filter)	Cyan	No visible change	7 or greater
	Magenta	No visible change.	7 or greater
	Yellow	Patch rapidly faded on exposure to light, fading to a lighter tone.	4
	Black	Ink patch faded rapidly on exposure and underwent colour change turning to a pale orange colour (see fig. 5.13).	3
	Paper	Paper slightly yellowed.	N/A
1.2 (uncovered)	Cyan	Patch faded to a lighter tone.	4
	Magenta	No visible change.	7 or greater
	Yellow	Patch rapidly faded on exposure to light, fading to a lighter tone.	3
	Black	Ink patch faded rapidly on exposure and underwent colour change turning to a pale orange colour (see fig. 5.13).	1
	Paper	Paper slightly yellowed.	N/A

Table 5.8 Continued

Sample No.	*Ink Patch*	*Observations after light ageing under ambient light conditions*	*Blue Wool Scale Rating (1-7)*
1.2 (covered with a UV filter)	Cyan	Patch faded to a lighter tone.	4
	Magenta	No visible change.	7 or greater
	Yellow	Patch rapidly faded on exposure to light, fading to a lighter tone.	4
	Black	Ink patch faded rapidly on exposure and underwent colour change turning to a pale orange colour (see fig. 5.13).	2
	Paper	Paper slightly yellowed.	N/A

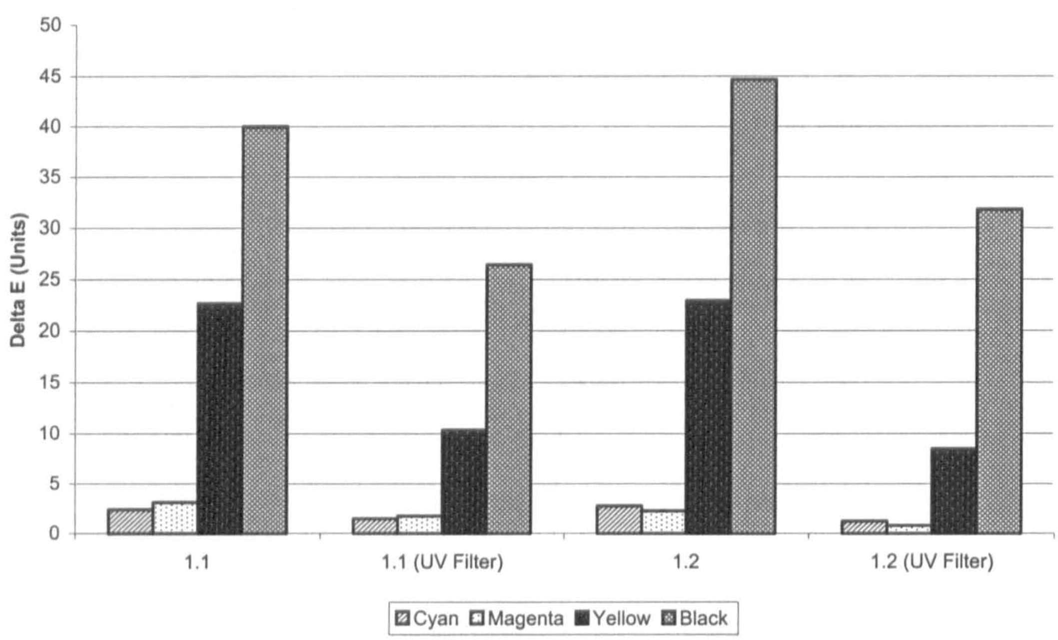

Fig. 5.13 Bar chart showing ΔE_{ab} after exposure to daylight for 50,863 klux hours for the Iris Morgan FA ink set printed on Inveresk Somerset paper (1.1) and Whatman watercolour paper (1.2), with and without a UV filter. Graphs of fading rates of the inks are shown in Appendix H (pg. H - 369 to H - 382).

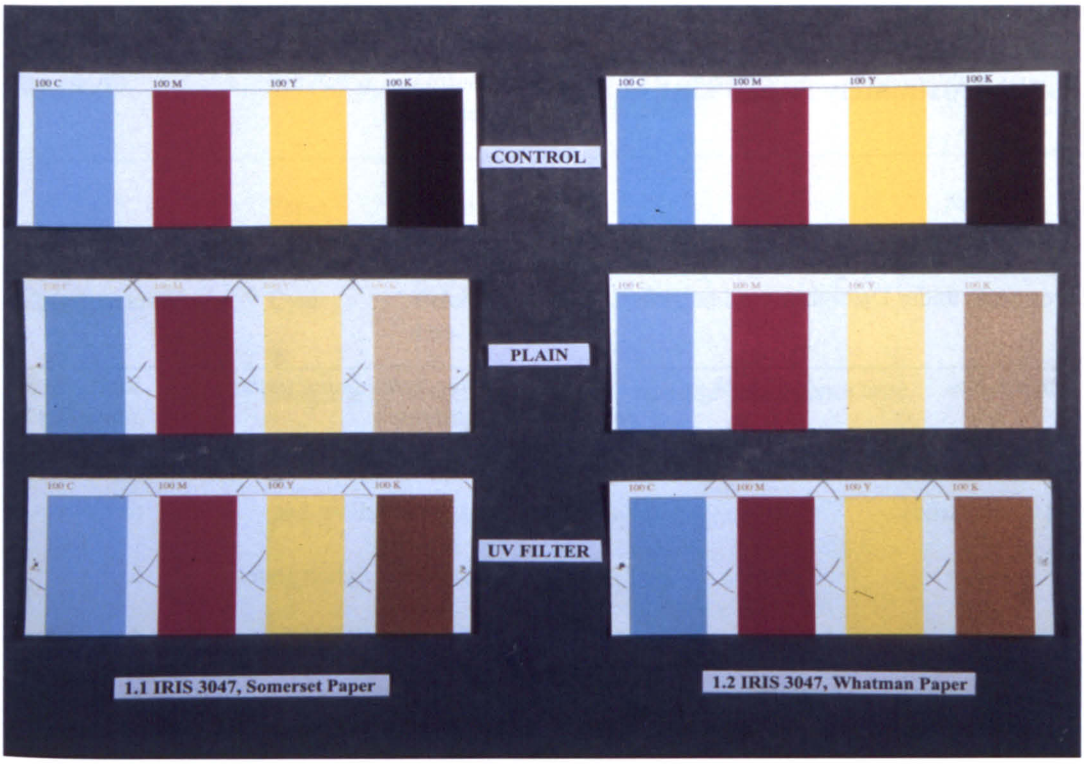

Fig. 5.14 Photograph of the Iris Morgan FA samples printed on the Somerset Velvet (1.1) and Whatman watercolour papers (1.2) after exposure to natural daylight for 50,863 klux hours, unfiltered (marked as plain) and with a UV filter. The samples are compared to two of the blue wool scales that were exposed alongside the samples, unfiltered (marked as plain) and with a UV filter.

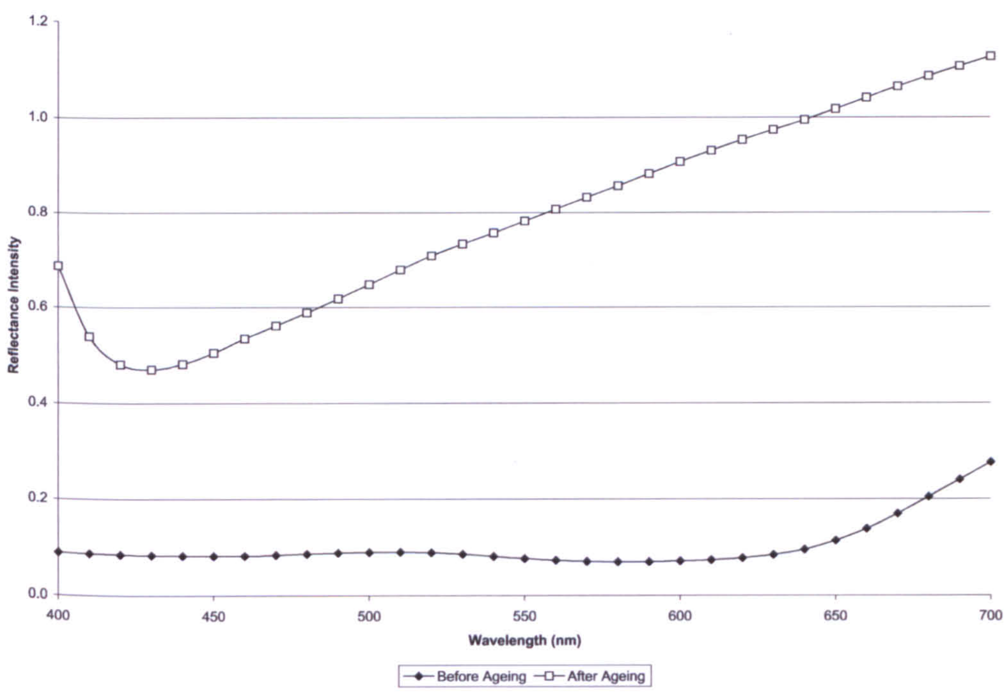

Fig. 5.15 Plot showing the change in reflectance spectra of Iris black ink printed on Whatman paper after exposure to daylight for 50,863 klux hours unfiltered.

5.3.3 Results of the Lyson print samples after light ageing in natural daylight for approximately 50,863 klux hours

Table 5.9 Visual observations of Lyson print samples under ambient light conditions, and comparison of the degree of fading of the samples to a blue wool scale using the BS 1006 (A02) grey scale under D_{50} lighting.

Sample No.	*Ink Patch*	*Observations after light ageing under ambient light conditions*	*Blue Wool Scale Rating (1-7)*
2.1 (uncovered)	Cyan	Patch faded, and has a yellow hue.	6
	Magenta	Patch faded slightly to a lighter tone.	5
	Yellow	Patch faded slightly to a lighter tone.	4
	Black	Patch faded slightly.	5
	Paper	Paper yellowed slightly.	N/A
2.1 (covered with a UV filter)	Cyan	No visible change.	7 or greater
	Magenta	No visible change.	7 or greater
	Yellow	Patch faded slightly.	6
	Black	No visible change.	7 or greater
	Paper	No visible change.	N/A
2.2 (uncovered)	Cyan	Patch faded very slightly, and has a yellow hue.	5
	Magenta	Patch faded slightly to a lighter tone.	4
	Yellow	Patch faded slightly to a lighter tone.	5
	Black	Patch faded very noticeably, changing to an orange/grey colour.	3
	Paper	Paper yellowed slightly.	N/A
2.2 (covered with a UV filter)	Cyan	No visible change.	7 or greater
	Magenta	No visible change.	6
	Yellow	No visible change.	6
	Black	Patch faded very noticeably, changing to a dark orange/grey colour.	4

Table 5.9 Continued

Sample No.	*Ink Patch*	*Observations after light ageing under ambient light conditions*	*Blue Wool Scale Rating (1-7)*
	Paper	No visible change.	N/A
2.3 (uncovered)	Cyan	Patch faded very slightly and has a yellow hue.	4
	Magenta	Patch faded slightly to a lighter magenta tone.	4
	Yellow	Patch faded slightly to a lighter yellow tone.	5
	Black	Patch faded slightly to a lighter tone.	4
	Paper	Paper yellowed slightly.	N/A
2.3 (covered with a UV filter)	Cyan	No visible change.	5
	Magenta	Patch faded very slightly.	5
	Yellow	No visible change.	5
	Black	No visible change.	4
	Paper	Paper yellowed slightly.	N/A
2.4 (uncovered)	Cyan	Patch faded very slightly and has a yellow hue.	5
	Magenta	Patch faded to a lighter magenta tone.	4
	Yellow	Patch slightly darker than control.	5
	Black	Patch faded to a lighter tone, and has an orange hue.	3
	Paper	Paper yellowed slightly.	N/A
2.4 (covered with a UV filter)	Cyan	No visible change.	5
	Magenta	Patch faded to a lighter magenta tone.	5
	Yellow	Patch slightly darker than control.	5
	Black	Patch faded to a lighter tone, and has an orange hue.	4
	Paper	Paper yellowed slightly.	N/A

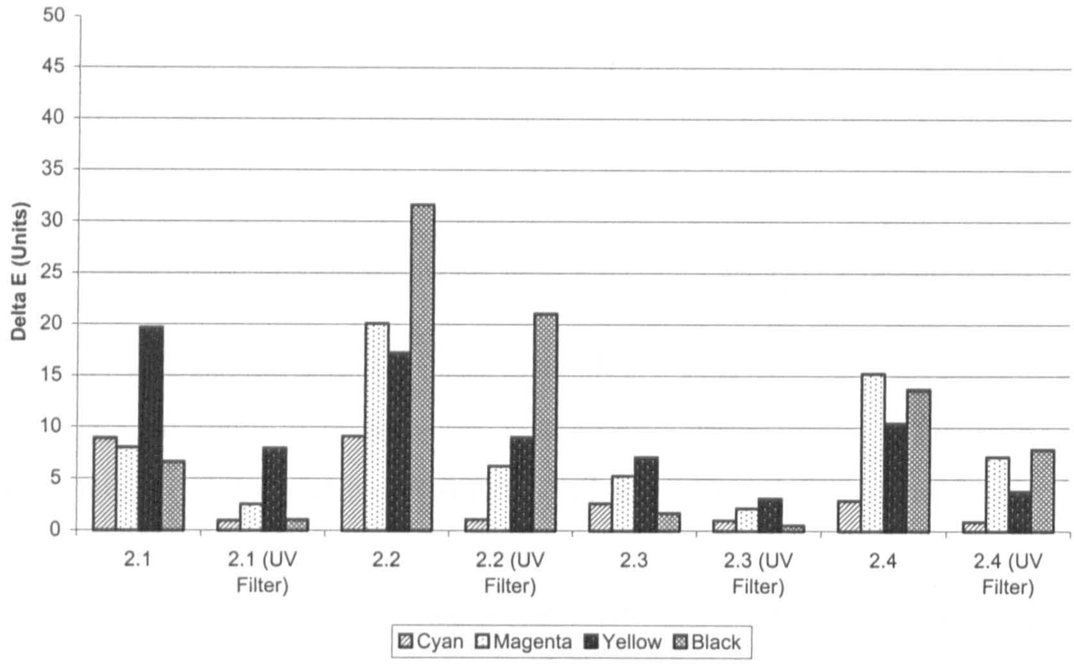

Fig. 5.16 Bar chart showing ΔE_{ab} after exposure to daylight for 50,863 klux hours for samples of the Lysonic ink set printed on Soft Fine Art Watercolour paper (2.1), and Whatman paper (2.3), and the Fotonic ink set on Rough Fine Art Watercolour paper (2.2) and Whatman paper (2.4), with and without an UV filter.

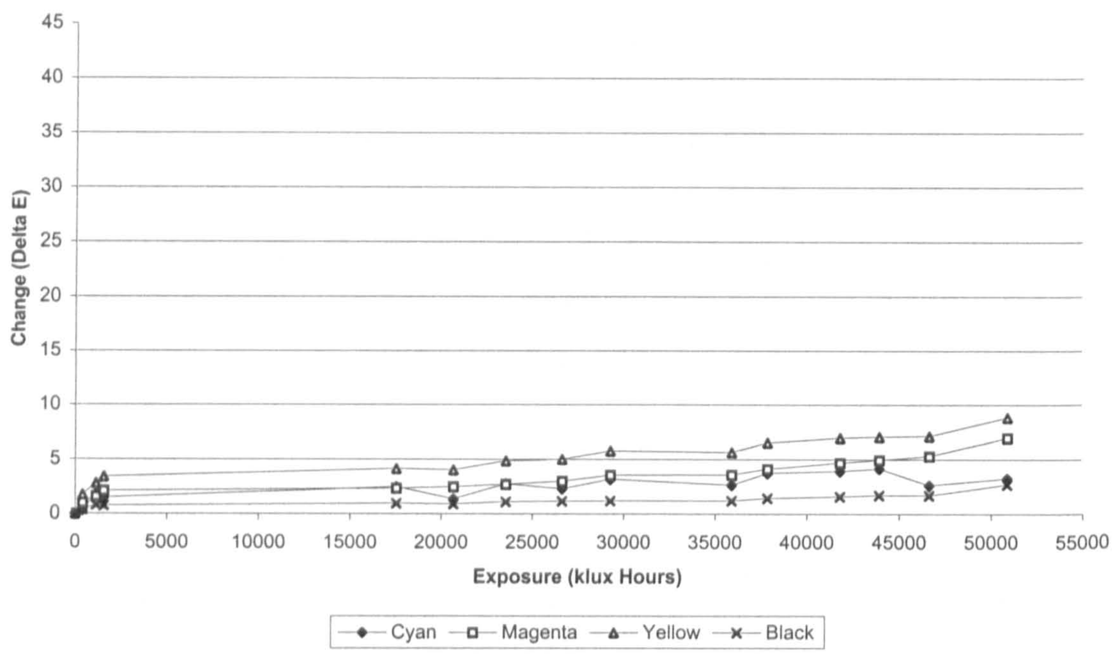

Fig. 5.17 Plot showing the change in ΔE_{ab} against exposure of the Fotonic ink set printed on Whatman watercolour paper (2.3) exposed under an UV filter. The yellow ink shows an uneven fading rate, further test concluded that the ink is photochromatic (see 5.6).

5.3.4 Results of the Epson print samples after light ageing in natural daylight for approximately 50,863 klux hours

Table 5.10 Visual observations of Epson print samples under ambient light conditions, and comparison of the degree of fading of the samples to a blue wool scale using the BS 1006 (A02) grey scale under D_{50} lighting.

Sample No.	*Ink Patch*	*Observations after light ageing under ambient light conditions*	*Blue Wool Scale Rating (1-7)*
3.1 (uncovered)	Cyan	Patch faded noticeably, changing to a pale tone.	4
	Magenta	Patch faded noticeably, changing to a pale tone.	3
	Yellow	Patch faded slightly.	6
	Black	Patch faded, and had a slight orange hue.	5
	Paper	Paper yellowed slightly.	N/A
3.1 (covered with a UV filter)	Cyan	Patch does not appear to have faded, but has a slight yellow hue.	6
	Magenta	Patch faded, changing to a lighter tone.	5
	Yellow	No visible change.	7 or greater
	Black	Patch has faded very slightly.	6
	Paper	Paper yellowed slightly.	N/A
3.2 (uncovered)	Cyan	Patch faded noticeably, changing to a much paler cyan tone.	2
	Magenta	Patch faded noticeably, changing to a much paler tone – the patch almost is the colour of the paper.	1
	Yellow	Patch faded noticeably, changing to a much paler tone.	4
	Black	Patch faded noticeably, changing to a lighter tone and had a slight yellow/orange hue.	2
	Paper	Paper yellowed slightly.	N/A

Table 5.10 Continued

Sample No.	*Ink Patch*	*Observations after light ageing under ambient light conditions*	*Blue Wool Scale Rating (1-7)*
3.2 (covered with a UV filter)	Cyan	Patch faded noticeably, changing to a paler tone.	3
	Magenta	Patch faded noticeably, changing to a much paler tone.	1
	Yellow	No visible change	7 or greater
	Black	Patch faded noticeably, change to a lighter tone and had a slight yellow/orange hue.	3
	Paper	Paper yellowed slightly.	N/A
3.4 (uncovered)	Cyan	Patch faded noticeably, changing to a pale tone.	3
	Magenta	Patch faded noticeably, changing to a pale tone.	2
	Yellow	Patch faded noticeably, change to a pale tone.	2
	Black	Patch faded noticeably, change to a lighter tone and had a slight yellow/orange hue.	4
	Paper	Paper yellowed slightly.	N/A
3.4 (covered with a UV filter)	Cyan	Patch faded noticeably, changing to a pale tone.	3
	Magenta	Patch faded noticeably, changing to a pale tone.	2
	Yellow	Patch faded noticeably, change to a lighter tone.	4
	Black	Patch faded noticeably, change to a lighter tone, which had a slight yellow/orange hue.	5
	Paper	Paper yellowed slightly.	N/A

Table 5.10 Continued

Sample No.	*Ink Patch*	*Observations after light ageing under ambient light conditions*	*Blue Wool Scale Rating (1-7)*
3.6 (uncovered)	Cyan	Patch faded noticeably, changing to a pale blue tone.	4
	Magenta	Patch faded noticeably, changing to a lighter tone with a slight orange hue.	5
	Yellow	Patch faded slightly.	5
	Black	Patch faded slightly.	6
	Paper	Paper yellowed slightly.	N/A
3.6 (covered with a UV filter)	Cyan	Patch faded to a lighter tone.	5
	Magenta	Patch faded to a lighter tone.	6
	Yellow	Patch faded very slightly.	6
	Black	No visible change.	7 or greater
	Paper	Paper yellowed very slightly.	N/A

Three of the five papers tested with the Epson Pro 9000 were printed in time for the beginning of the natural ageing tests. They were the Epson Photo Glossy paper, the Whatman Watercolour paper and the ISVE paper. After light ageing, the difference in fading of the inks between the coated and uncoated papers was vast, with the coated papers out performing the uncoated papers.

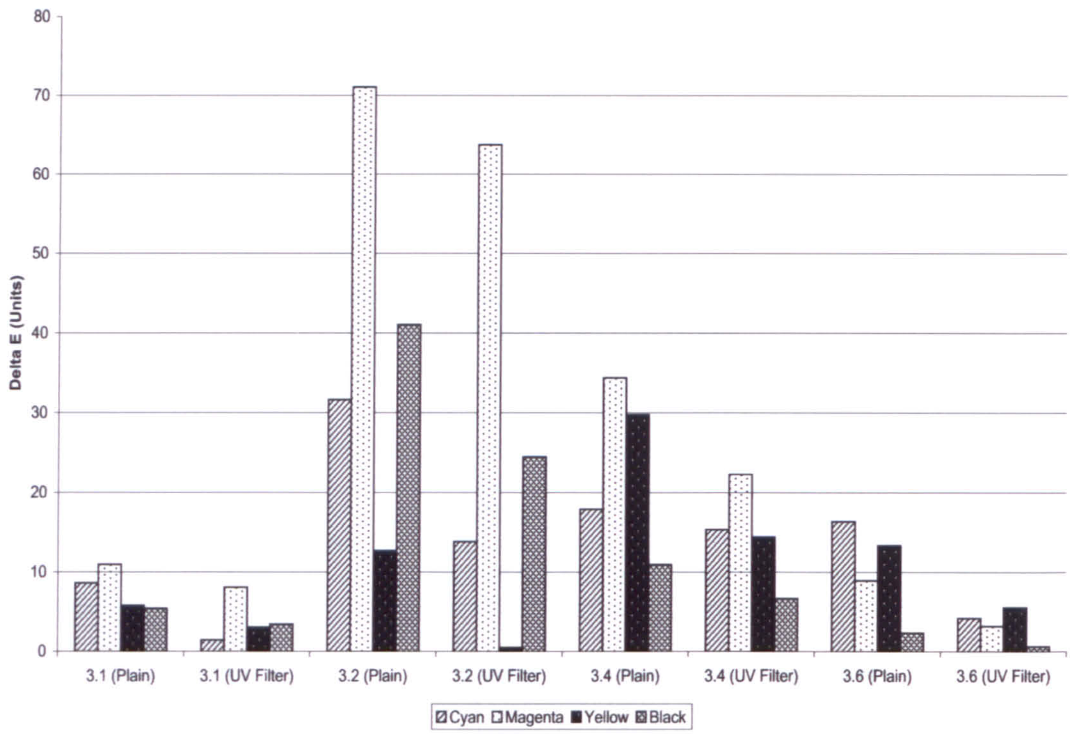

Fig. 5.18 Bar chart showing ΔE_{ab} after exposure to daylight for 50,863 klux hours for the Epson Pro 9000 ink set printed on Epson Photo Glossy paper (3.1), IVSE paper (3.2), Whatman watercolour paper (3.4), and the Epson Photo Stylus ink set on Epson Photo Glossy paper (3.6), with and without an UV filter.

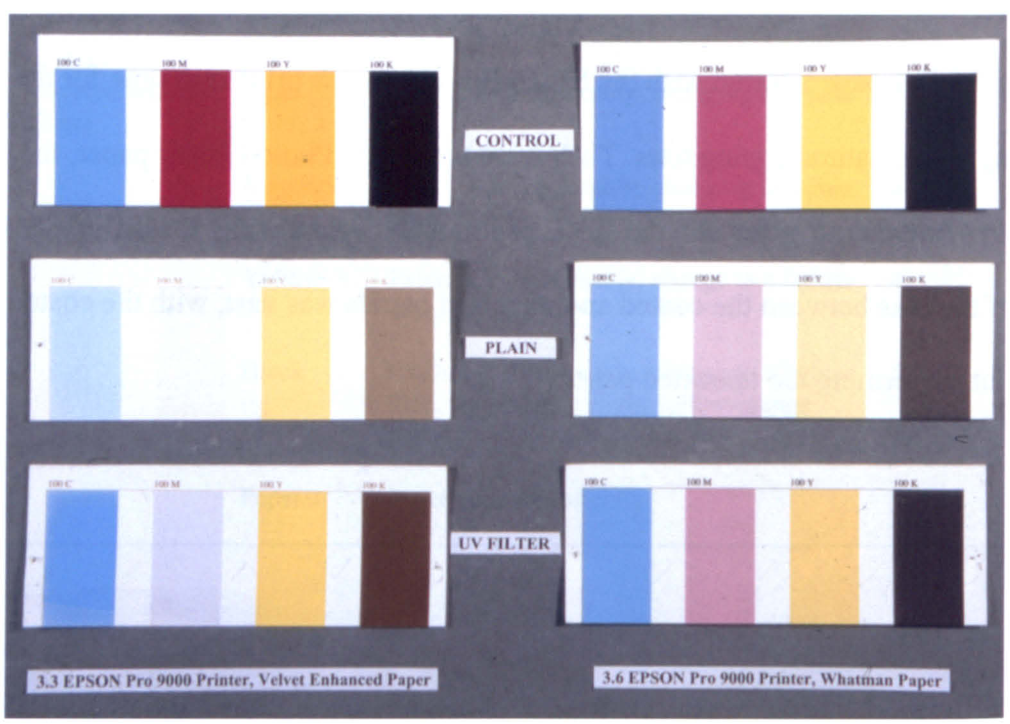

Fig. 5.19 Photograph of the Epson Pro 9000 print samples produced on ISVE (3.2) and Whatman watercolour paper (3.4) after exposure to natural daylight, with and without a UV filter. The magenta ink is the most sensitive to light for the Pro 9000 printed samples.

5.3.5 Results of the Hewlett Packard print samples after light ageing in natural daylight for approximately 50,863 klux hours

Table 5.11 Visual observations of Hewlett Packard print samples under ambient light conditions, and comparison of the degree of fading of the samples to a blue wool scale using the BS 1006 (A02) grey scale under D_{50} lighting.

Sample No.	*Ink Patch*	*Observations after light ageing under ambient light conditions*	*Blue Wool Scale Rating (1-7)*
4.1 (uncovered)	Cyan	Patch faded to a much lighter tone.	3
	Magenta	Patch faded to a pale magenta tone.	2
	Yellow	Patch faded to a pale yellow tone.	3
	Black	Patch faded to a much lighter tone.	3
	Paper	Paper yellowed slightly.	N/A
4.1 (covered with a UV filter)	Cyan	Patch faded to a lighter tone.	5
	Magenta	Patch faded to a much lighter tone.	4
	Yellow	No visible change.	6
	Black	Patch faded to a slightly lighter tone.	4
	Paper	Paper yellowed slightly.	N/A

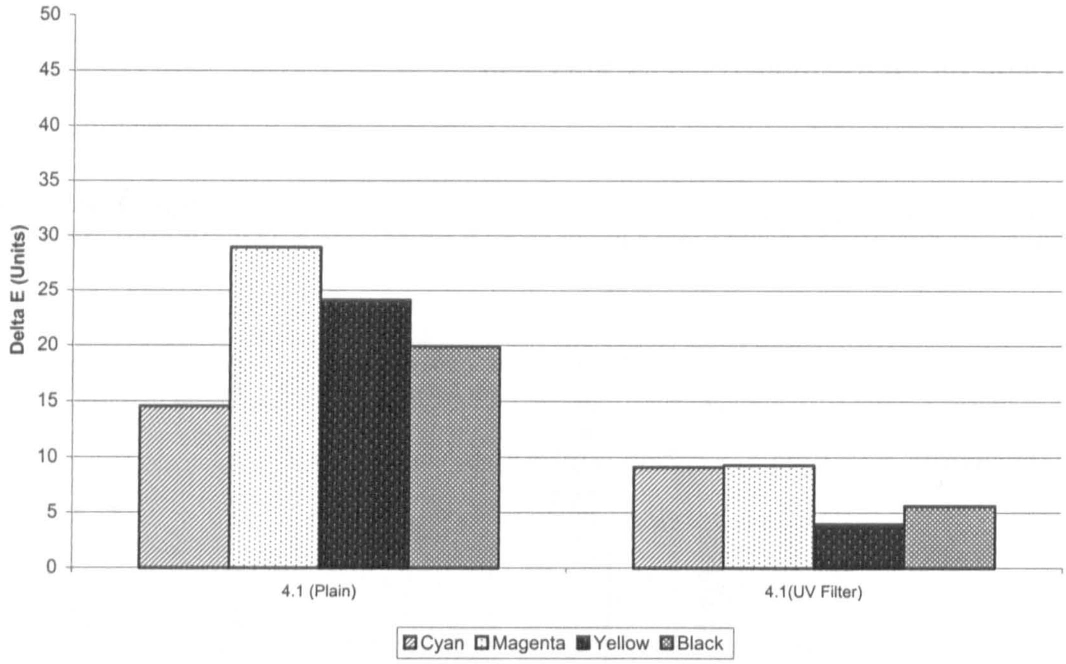

Fig. 5.20 Bar chart showing ΔE_{ab} after exposure to daylight for 50,863 klux hours for the Hewlett Packard samples printed on Hewlett Packard Coated Matt paper (4.1), with and without a UV filter.

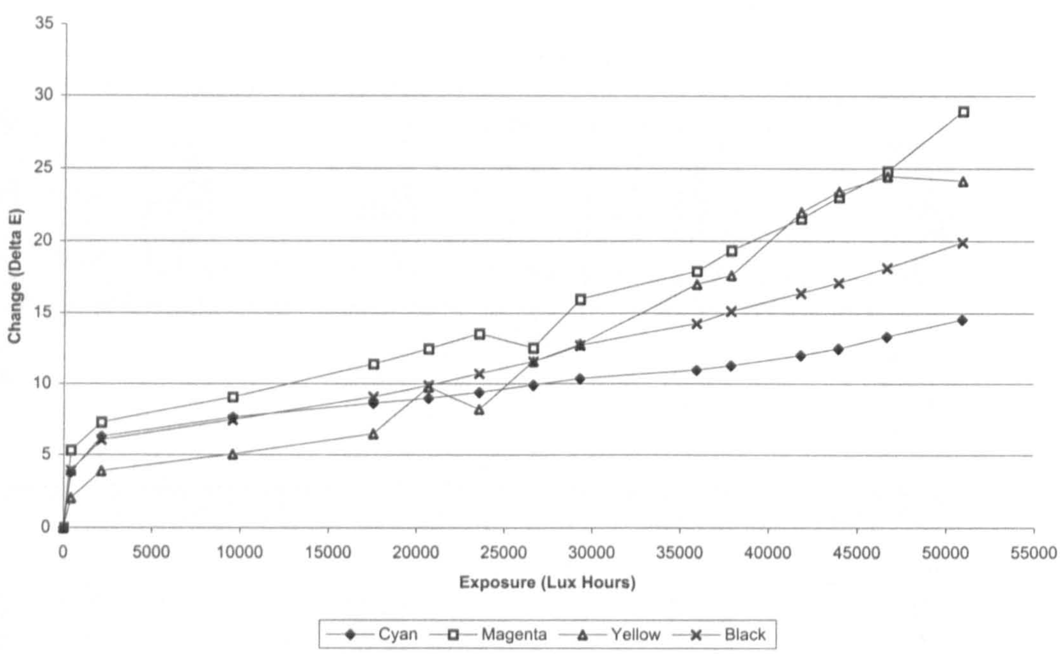

Fig. 5.21 Plot to show the fading rate of the Hewlett Packard printed sample exposed to natural daylight unfiltered. The yellow ink has an uneven fading rate further testing showed that the ink is photochromatic (see 5.6).

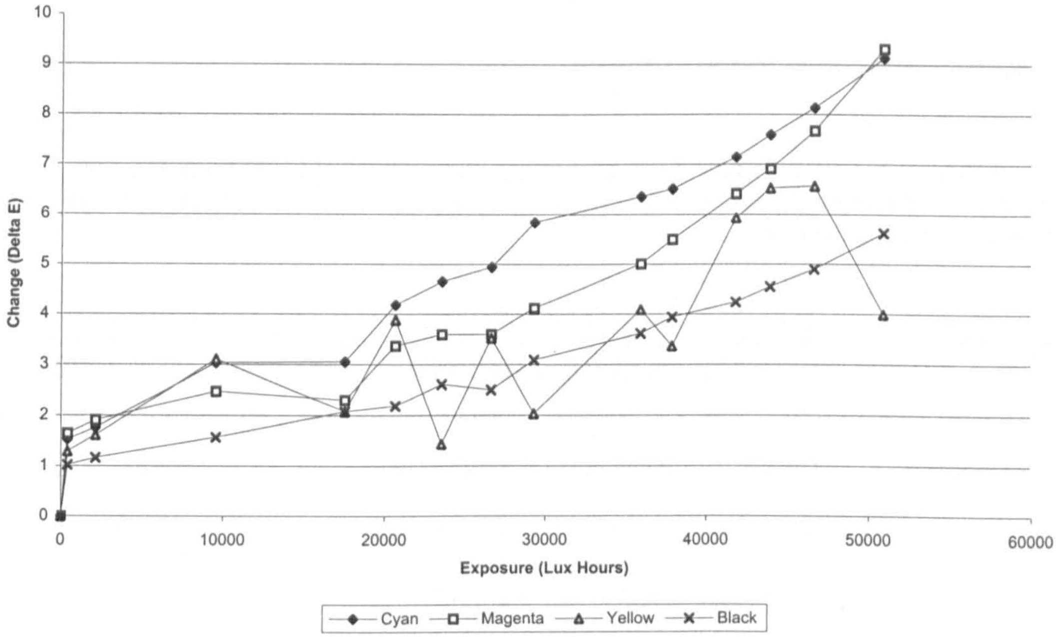

Fig. 5.22 Plot showing the change in ΔE_{ab} against exposure of the Hewlett Packard printed sample exposed to natural daylight under an UV filter. All the inks show an improved stability under the filter. The cyan ink was the most sensitive ink to light from the ink set on the UV filtered sample. However, on the unfiltered sample, the magenta ink showed the most rapid fading rate (see fig. 5.21). The UV filtered yellow ink patch has a more uneven fade rate than the same ink patch exposed unfiltered (see fig. 5.21).

5.3.6 Results of the Canon print samples after light ageing in natural daylight for approximately 50,863 klux hours

Table 5.12 Visual observations of Canon print samples under ambient light conditions, and comparison of the degree of fading of the samples to a blue wool scale using the BS 1006 (A02) grey scale under D_{50} lighting.

Sample No.	*Ink Patch*	*Observations after light ageing under ambient light conditions*	*Blue Wool Scale Rating (1-7)*
5.1 (uncovered)	Cyan	Patch faded to a lighter tone.	5
	Magenta	Patch faded to a lighter tone.	4-5
	Yellow	Patch faded slightly, to a lighter tone.	6
	Black	No visible change.	7 or greater
	Paper	Paper yellowed.	N/A
5.1 (covered with a UV filter)	Cyan	Patch faded to a slightly lighter tone.	6
	Magenta	Patch faded to a slightly lighter tone.	6
	Yellow	No visible change.	7 or greater
	Black	No visible change.	7 or greater
	Paper	Paper yellowed slightly.	N/A
5.2 (uncovered)	Cyan	Patch shows a small degree of fading and has a slight yellow hue.	6
	Magenta	Patch shows a small degree of fading and has a slight orange hue.	6
	Yellow	Patch faded to a lighter tone.	5
	Black	No visible change.	7 or greater
	Paper	Paper yellowed.	N/A
5.2 (covered with a UV filter)	Cyan	No visible change.	7 or greater
	Magenta	No visible change.	7 or greater
	Yellow	Patch faded to a lighter tone.	5
	Black	No visible change.	7 or greater
	Paper	Paper yellowed slightly.	N/A

Table 5.12 Continued

Sample No.	*Ink Patch*	*Observations after light ageing under ambient light conditions*	*Blue Wool Scale Rating (1-7)*
5.3 (uncovered)	Cyan	Patch faded to a lighter tone and has a slight yellow hue.	4
	Magenta	Patch has faded to a lighter tone and has a slight orange hue.	5
	Yellow	Patch faded slightly, to a lighter tone.	6
	Black	No visible change.	7 or greater
	Paper	Paper yellowed	N/A
5.3 (covered with a UV filter)	Cyan	Patch faded to a lighter tone and has a slight yellow hue.	5
	Magenta	Patch has faded to a lighter tone and has a slight orange hue.	6
	Yellow	No visible change.	7 or greater
	Black	No visible change.	7 or greater
	Paper	Paper yellowed slightly.	N/A
5.4 (uncovered)	Cyan	Patch faded to a slightly lighter tone	6
	Magenta	Patch faded to a lighter tone.	5
	Yellow	Patch faded to a slightly lighter tone	6
	Black	No visible change.	7 or greater
	Paper	Paper yellowed.	N/A
5.4 (covered with a UV filter)	Cyan	No visible change	7 or greater
	Magenta	Patch faded to a lighter tone.	5-6
	Yellow	No visible change.	7 or greater
	Black	No visible change.	7 or greater
	Paper	Paper yellowed slightly.	N/A
5.5 (uncovered)	Cyan	Patch faded to a slightly lighter tone	6
	Magenta	Patch faded to a lighter tone.	5
	Yellow	No visible change.	7 or greater
	Black	No visible change.	7 or greater
	Paper	Paper yellowed.	N/A

Table 5.12 Continued

Sample No.	*Ink Patch*	*Observations after light ageing under ambient light conditions*	*Blue Wool Scale Rating (1-7)*
5.5 (covered with a UV filter)	Cyan	No visible change.	7 or greater
	Magenta	Patch faded to a slightly lighter tone.	6-7
	Yellow	No visible change.	7 or greater
	Black	No visible change.	7 or greater
	Paper	Paper yellowed slightly.	N/A

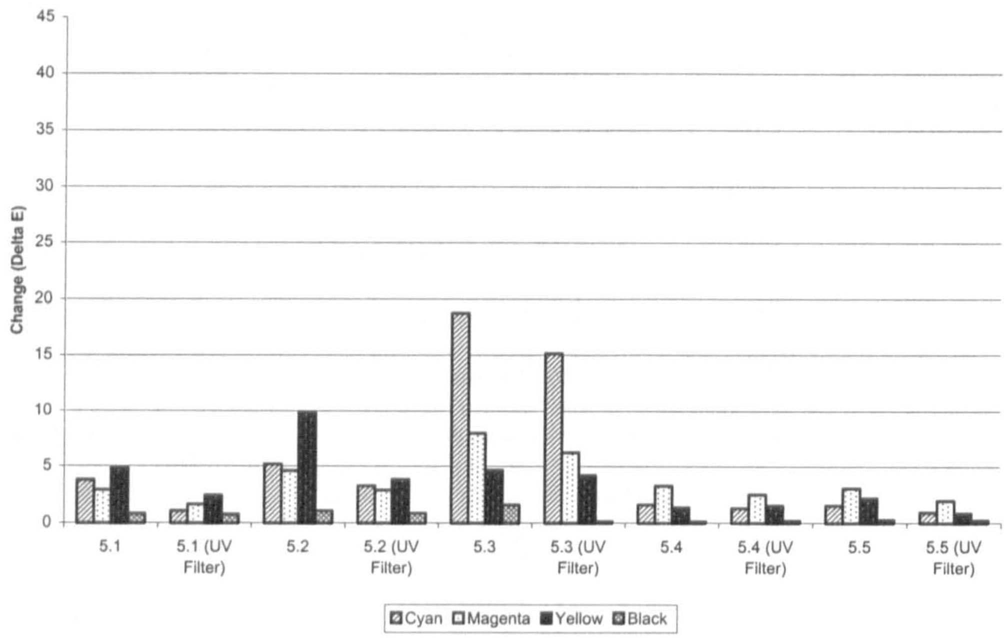

Fig. 5.23 Bar chart showing ΔE_{ab} after exposure to daylight for 50,863 klux hours for samples of Canon printing with the 1150 printer on Ultra White paper Card (5.1 and 5.2), CLC 900 printer on Ultra White paper and Card (5.3 and 5.4) and the CLBP 400 PS printer on Ultra White paper (5.5), with and without a UV filter.

5.4 TUNGSTEN – HALOGEN LIGHT FASTNESS TESTING

5.4.1 Test conditions

Table 5.13 Environmental conditions recorded for the halogen light test.

Week No.	*Cumulative Exposure (klux Hours)*	*Temperature Range (°C)*	*Relative Humidity Range (%)*
1	168	21-25	39-69
2	336	21-30	55-75
3	504	20-24	52-72
4	672	19-23	51-69
5	840	17-21	48-56
6	1,008	18.5-22	42-59
7	1,176	15-24	55-68
8	1,344	16-21.5	45-56
9	1,512	15-21.5	45-57

The black panel temperature increased to 1 °C above room temperature occasionally otherwise it remained at room temperature. Unfortunately, due to unforeseen circumstances with the electricity supply to the Camberwell College of Arts, the halogen light apparatus was turned off after week nine and testing had to be discontinued.

5.4.2 Visual examination of Iris print samples after light ageing

Table 5.14 Visual observations of Iris print samples under ambient light conditions after light ageing in the tungsten-halogen light fastness test for approximately 1,512 klux hours.

Sample No.	*Ink Patch*	*Observations after light ageing under ambient light conditions*
1.1	Cyan	Patch faded slightly, and has a yellow hue.
	Magenta	No visible change.
	Yellow	No visible change.
	Black	Ink patch faded slightly, and has an orange hue.
	Red	No visible fading.
	Green	No visible fading.
	Blue	No visible fading.
	25/50 % CMY	Patches have very slightly lightened.
	25/50 % CMYK	Patches had faded slightly, and have a grey/brown tone.
	Paper	Paper very slightly yellowed.
1.2	Cyan	Patch faded slightly, and has a yellow hue.
	Magenta	No visible change.
	Yellow	No visible change.
	Black	Ink patch faded noticeably, and has an orange hue.
	Red	No visible fading.
	Green	No visible fading.
	Blue	No visible fading.
	25/50 % CMY	Patches have very slightly lightened.
	25/50 % CMYK	Patches had faded slightly, and have a grey/brown tone.
	Paper	Paper very slightly yellowed.

Limited space on the exposure area meant that only a selection of colour patches from the two Iris sample sets were exposed to the tungsten-halogen light test.

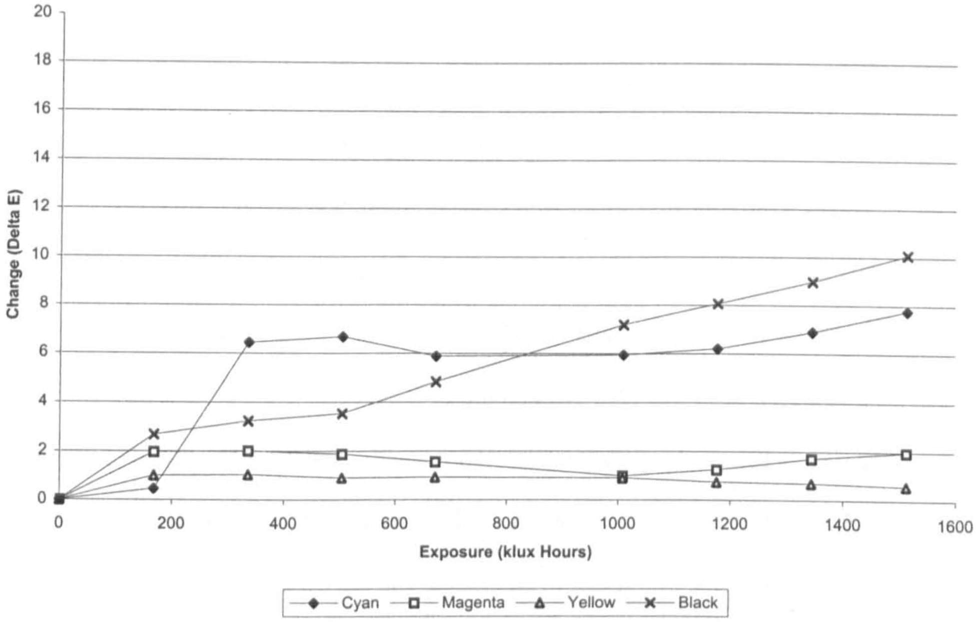

Fig. 5.24 Plot showing the change in ΔE_{ab} against exposure of the Iris Morgan FA ink set printed on Whatman watercolour paper (1.2) on exposure to tungsten halogen light.

5.4.3 Visual examination of Epson print samples after light ageing

Table 5.15 Visual observations of Epson print samples under ambient light conditions after light ageing in the tungsten-halogen light fastness test for approximately 1,512 klux hours.

Sample No.	*Ink Patch*	*Observations after light ageing under ambient light conditions*
3.1	Cyan	Patch faded very noticeably, turning a paler tone.
	Magenta	Patch faded slightly, becoming lighter in tone.
	Yellow	No visible fading.
	Black	No visible fading.
	Red	Patch slightly lighter in tone.
	Green	Patch faded, becoming lighter in tone.
	Blue	Patch faded, becoming lighter in tone.
	100 % C 50 % K	Patch faded noticeably, becoming lighter in tone.

Table 5.15 Continued

Sample No.	*Ink Patch*	*Observations after light ageing under ambient light conditions*
	100 % M 50 % K	Patch faded, becoming lighter in tone.
	100 % Y 50 % K	Patch faded, becoming lighter in tone.
	25/50 % C	Patches faded very noticeably, turning a paler tone.
	25/50 % M	Patches faded slightly, becoming lighter in tone.
	25/50 % Y	No visible fading.
	25/50 % K	Patches faded noticeably, and have an orange/brown tone.
	25/50 % CMY	Patches had faded, and have a yellow/brown tone.
	25/50 % CMYK	Patches had faded, and have a yellow/brown tone.
	Paper	Paper slightly yellowed.
3.2	Cyan	Patch has faded very noticeably, and turned a pale blue tone.
	Magenta	Patch has faded very noticeably, and turned a pale magenta tone.
	Yellow	Patch has faded very noticeably, and turned a pale yellow tone.
	Black	Patch has faded, and has an orange hue.
	Paper	Paper slightly yellowed.

Limited space on the exposure area meant that only two different papers from the Epson Pro 9000 printed samples were tested with this apparatus: The Epson Photo Glossy paper and the ISVE paper (3.1 and 3.2). The fading rate of the yellow ink printed on the Epson Photo Glossy paper showed an irregular fading rate (Appendix I (pp. I - 388)). Further testing showed that these inks are photochromatic (see 5.6).

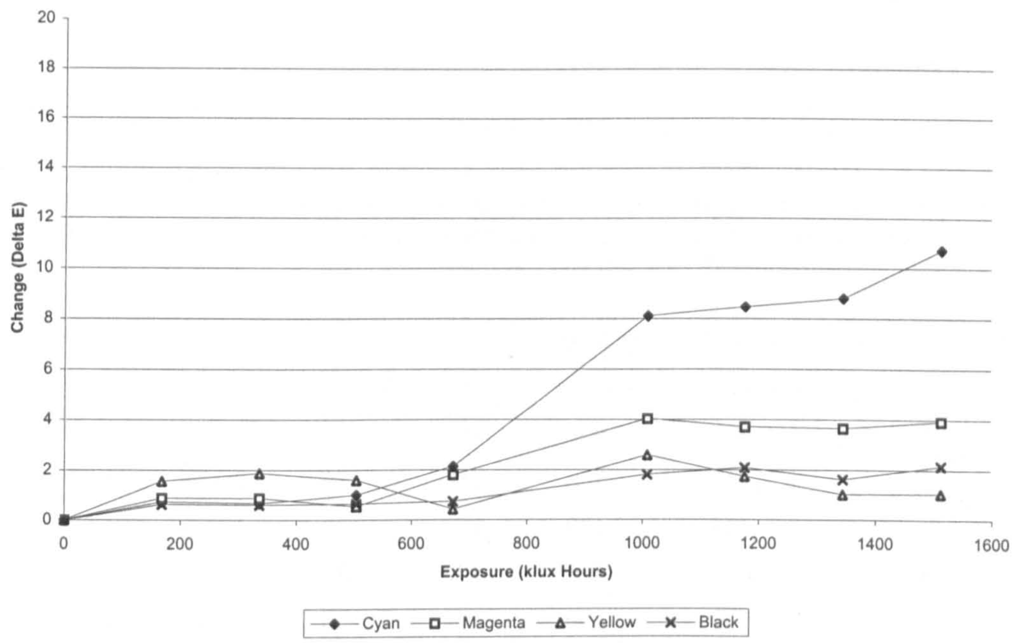

Fig. 5.25 Plot showing the change in ΔE_{ab} against exposure of the CMYK inks from the Epson Pro 9000 printed on Epson Photo Glossy paper (3.1) on exposure to the halogen light test.

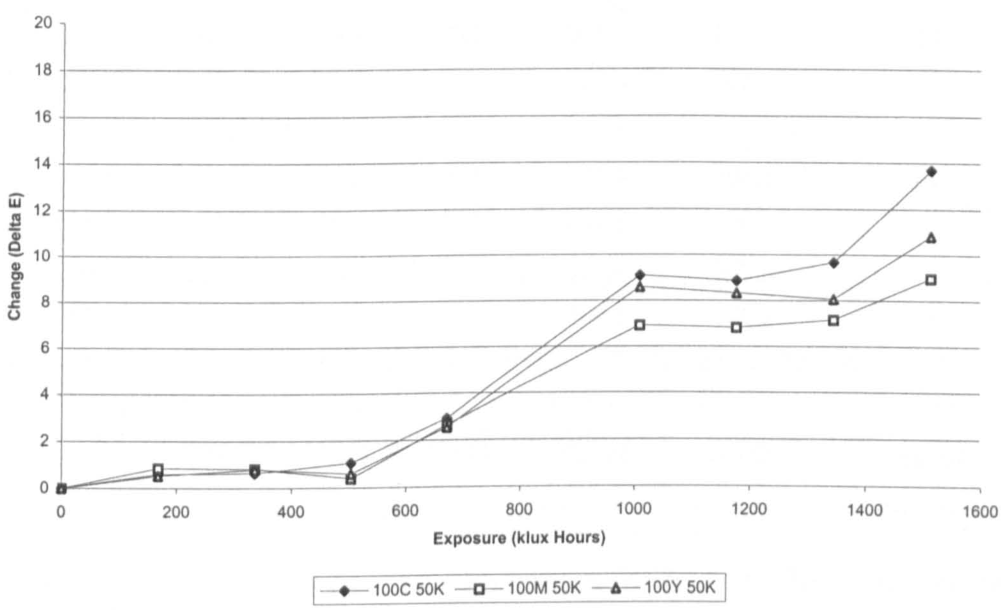

Fig. 5.26 Plot showing the change in ΔE_{ab} against exposure of the composite ink patches of the cyan, magenta and yellow inks printed with 50 % black for the Epson Pro 9000 sample printed on Epson Photo Glossy paper (3.1).

5.5 FLUORESCENT LIGHT FASTNESS TESTING

5.5.1 Transmittance lux of UV and dichroic filters

Table 5.16 Lux levels of the fluorescent light tester measured at specific points over the sample exposure plane. Further measurements were then taken of the levels of lux transmitted through the UV and various dichroic coloured filters employed with the test at the same positions. All the dichroic filters were fitted with an additional UV filter.

Measurement No.	*Type of exposure (lux)*						
	Unfiltered	*UV Filter*	*Violet*	*Blue*	*Green*	*Orange*	*Yellow*
1	6,500	4,900	169	590	1,800	1,790	3,420
2	7,400	5,700	180	780	2,200	1,900	3,900
3	6,200	5,100	163	630	1,800	1,800	3,300
4	6,600	5,400	176	630	1,900	2,000	3,600
5	6,800	5,200	190	810	2,300	2,000	4,100
6	6,600	5,300	171	680	1,900	1,900	3,600
7	7,000	5,400	172	680	2,000	2,100	3,800
8	7,900	5,300	191	820	2,300	2,100	4,200
9	7,500	5,300	175	680	2,000	2,000	4,000
10	6,400	5,300	171	660	2,000	2,000	3,600
11	7,900	5,100	190	810	2,300	2,100	4,100
12	7,000	5,200	173	680	2,000	1,900	3,700
13	6,300	4,700	171	640	1,800	1,800	3,400
14	7,400	5,600	187	760	2,100	1,900	3,900
15	6,600	4,700	168	620	1,900	1,900	3,500
16	5,400	3,800	151	560	1,500	1,600	3,100
17	6,300	4,500	167	700	1,900	1,600	3,300
18	5,300	4,000	152	610	1,500	1,500	2,800
Mean	6,788.88	5,072.22	173.17	685.55	1,955.56	1,882.78	3,628.88
Standard Deviation	729.87	514.27	11.57	79.57	235.7	176.03	374.75

5.5.2 Test conditions

Table 5.17 Environment conditions recorded for the fluorescent light tester.

Week No.	*Temperature (°C)*	*Relative Humidity (%)*	*Approximate Cumulative Exposure (klux Hours)* UV Filter	*Violet*	*Blue*	*Green*	*Yellow*	*Orange*
1	23	59	852	29	115	328	316	609
2	25	59	1,704	58	230	657	633	1,219
3	24.5	55.5	2,556	87	346	986	949	1,829
4	23.5	56	3,408	116	461	1,314	1,265	2,439
5	23	55	4,260	145	576	1,643	1,582	3,048
6	25	55	5,113	175	691	1,971	1,898	3,658
7	23	54	5,965	204	806	2,300	2,214	4,268
8	24	56	6,817	233	921	2,628	2,530	4,877
9	22	56	7,669	261	1,037	2,957	2,847	5,487
10	25	55	8,521	291	1,152	3,285	3,163	6,097
11	24	53	9,373	320	1,267	-	-	-
12	25	56	10,802	349	1,382	-	-	-
13	23	56	-	378	1,497	-	-	-
14	22.5	55	-	407	1,612	-	-	-
15	23	54	-	436	-	-	-	-
16	24	56	-	465	-	-	-	-

Initially, all the samples were exposed to the fluorescent light box for ten weeks, then the samples exposed under the blue and violet filters were left in the tester for a further four and six weeks respectively, to compensate for the reduced amount of light being transmitted through these filters. The temperature under all the filters was 1 °C less than the ambient temperature in the box, and the black panel temperature had the same temperature as the other colour patches. The surface temperature of the samples covered with black card was 3 °C above the ambient temperature.

Every time the box was opened to remove the sample for colour measurement, the relative humidity levels in the box would fall by 10 % to 12 %. Once the samples were replaced and the box closed, it would take over six hours for the humidity to reach the desired level.

Calculation of the total exposure, H (in watts hours per square metre, Whm^{-2}) (see 4.3.10) of the samples under the filters revealed that, compared to the UV filters, the dichroic filters transmitted less light (see table 5.18).

Table 5.18 Amount of light transmitted by dichroic filters compared to the UV filter. All UV radiation was filtered from the dichroic filters.

Filter Type	*Wavelengths Transmitted (nm)*	*Total Exposure, H of Light Transmitted by Dichroic Filters (Whm^{-2})*	*Percentage Difference of light transmitted by Dichroic Filters Compared to the UV Filter*
U.V	400 - 700	518,977	-
Violet	400 – 455	75,884	Transmitted approximately 85 % less light.
Blue	400 – 500	92,430	Transmitted approximately 82 % times less light.
Green	400 – 570	112,117	Transmitted approximately 78 % times less light.
Yellow	400 – 410; 485 – 700	228,248	Transmitted approximately 56 % times less light
Orange	535 – 700	143,181	Transmitted approximately 72 % times less light.

5.5.3 Visual examination of Iris print samples after light ageing

Table 5.19 Visual observations of Iris print samples under ambient light conditions after light ageing in the fluorescent light fastness test, under an UV filter, for approximately 10 weeks or 8,521 klux hours.

Sample No.	*Ink Patch*	*Observations after light ageing under ambient light conditions*
1.1	Cyan	Patch faded to a paler tone.
	Magenta	No visible change.
	Yellow	No visible change.
	Black	Ink patch faded, and has an orange hue.
	Paper	No visible change.
1.2	Cyan	Patch faded to a paler tone.
	Magenta	No visible change.
	Yellow	No visible change.
	Black	Ink patch faded noticeably, and has an orange hue.
	Paper	Very slightly yellowed.

Due to the limited space in the Perspex exposure box, only the CMYK ink patches were tested for the IRIS samples printed on the Somerset and Whatman papers.

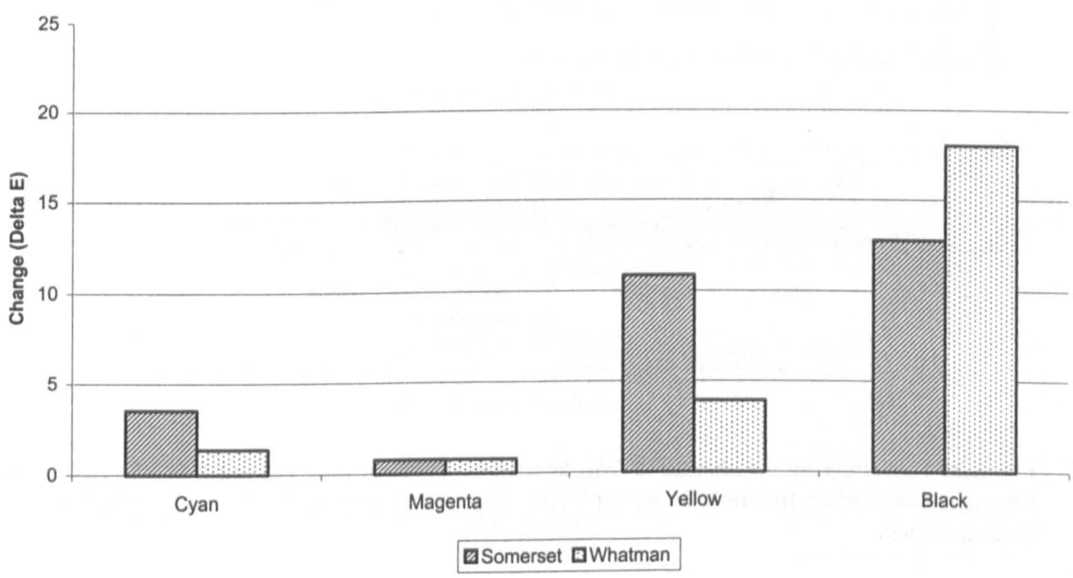

Fig. 5.27 Bar chart to compare the change in ΔE_{ab} of the Iris Morgan FA ink set printed on the Inveresk Somerset Velvet and Whatman watercolour papers (1.1 and 1.2), after exposure to the fluorescent light box under UV filters for 10 weeks or 8,521 klux hours.

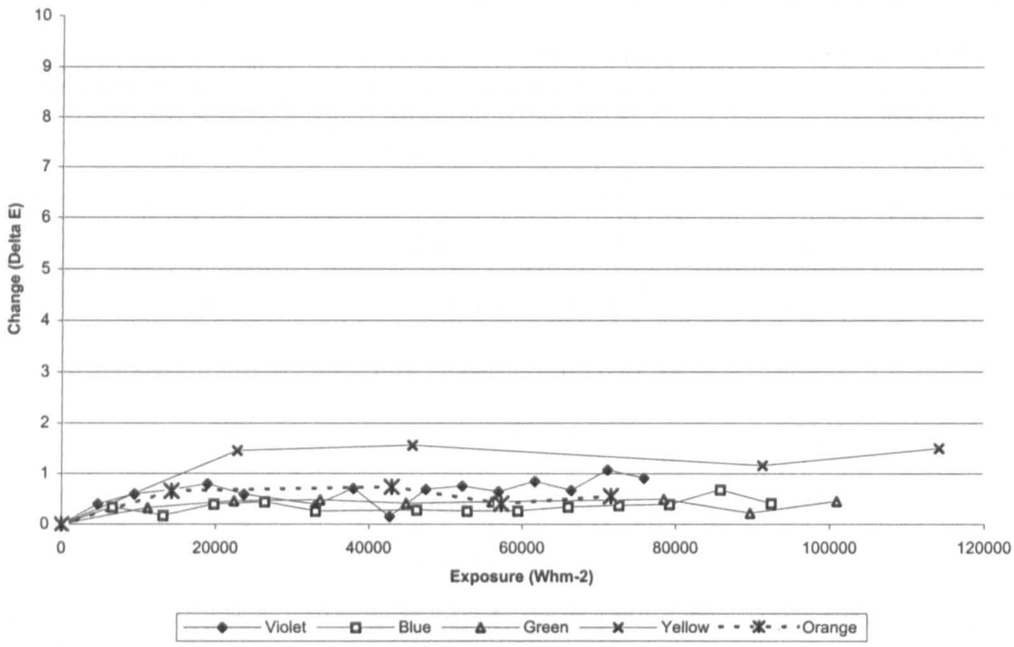

Fig. 5.28 Plot showing the change in ΔE_{ab} against exposure of the magenta ink patch from the Iris Morgan FA ink set printed on Whatman watercolour paper (1.2), exposed to fluorescent light under the dichroic filters.

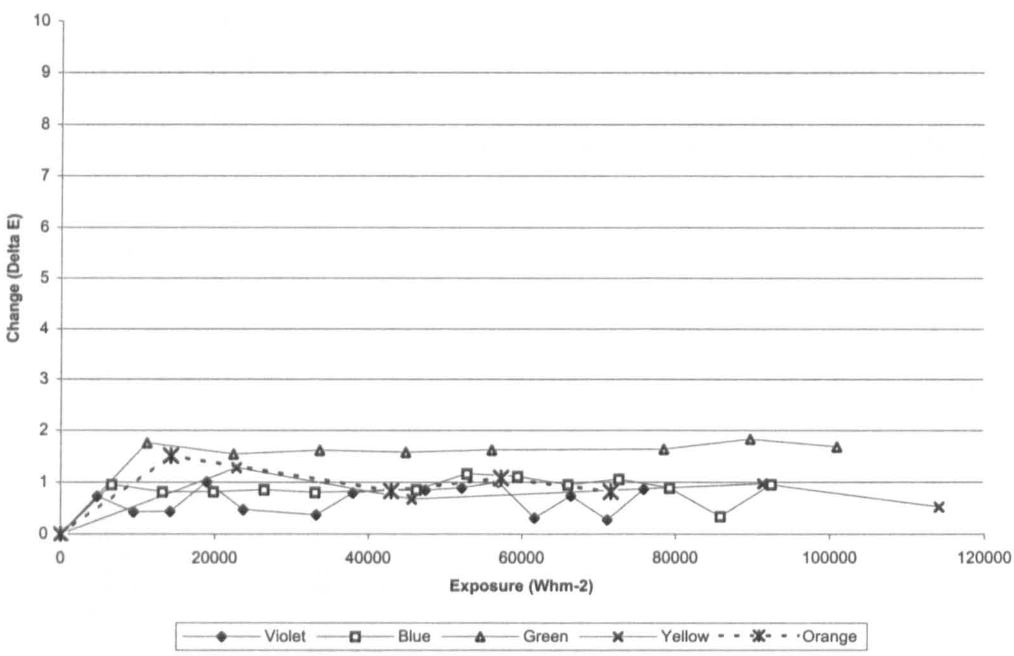

Fig. 5.29 Plot showing the change in ΔE_{ab} against exposure of the cyan ink from the Iris Morgan FA ink set printed on Inveresk Somerset Velvet paper (1.1), exposed to fluorescent light under the dichroic filters.

5.5.4 Visual examination of Epson print samples after light ageing

Table 5.20 Visual observations of Epson print samples under ambient light conditions after light ageing in the fluorescent light fastness test, under an UV filter, for approximately 12 weeks or 11,405 klux hours.

Sample No.	*Ink Patch*	*Observations after light ageing under ambient light conditions*
3.1	Cyan	Patch faded to a paler tone.
	Magenta	No visible change.
	Yellow	No visible change.
	Black	Ink patch faded, and has an orange hue.
	Paper	No visible change.
3.2	Cyan	No visible change.
	Magenta	Very slight fading
	Yellow	No visible change.
	Black	Patch has faded, and has an orange hue.
	Red	Patch has a slight yellow hue.
	Green	No visible change.
	Blue	Patch faded noticeably, changing to a lighter, bluer tone.
	25/50/75 % Cyan	No visible change.
	25/50/75 % Magenta	Patches faded to a lighter tone.
	25/50/75 % Yellow	No visible change.
	25/50/75 % Black	Patches faded noticeably, and changed colour from a mid-grey to a brown/grey.
	25/50 % CMY	Patches faded noticeably, and changed colour from a mid-grey to a pale green.
	25/50 % CMYK	Patches faded noticeably, and changed colour from a mid-grey to a pale green.
	Paper	No visible change.
3.3	Cyan	Patch faded slightly.
	Magenta	Patch faded to a light tone.
	Yellow	No visible change.
	Black	Patch has a slight orange hue.

Table 5.20 Continued

Sample No.	*Ink Patch*	*Observations after light ageing under ambient light conditions*
	Red	Patch faded to lighter tone.
	Green	No visible change.
	Blue	Patch faded to lighter bluer tone.
	25/50/75 % Cyan	Patches faded to a lighter tone.
	25/50/75 % Magenta	Patches faded to a lighter tone.
	25/50/75 % Yellow	No visible change.
	25/50/75 % Black	Patches faded noticeably, and changed colour from a mid-grey to a brown/grey.
	25/50 % CMY	Patches faded noticeably, and changed colour from a mid-grey to a pale green.
	25/50 % CMYK	Patches faded noticeably, and changed colour from a mid-grey to a pale green.
	Paper	No visible change.
3.4	Cyan	Patch faded slightly.
	Magenta	Patch faded to a light tone.
	Yellow	No visible change.
	Black	Patch has a slight orange hue.
	Red	Patch faded to lighter tone.
	Green	No visible change.
	Blue	Patch faded to lighter bluer tone.
	25/50/75 % Cyan	Patches faded to a lighter tone.
	25/50/75 % Magenta	Patches faded to a lighter tone.
	25/50/75 % Yellow	No visible change.
	25/50/75 % Black	Patches faded noticeably, and changed colour from a mid-grey to a brown/grey.
	25/50 % CMY	Patches faded noticeably, and changed colour from a mid-grey to a pale green.
	25/50 % CMYK	Patches faded noticeably, and changed colour from a mid-grey to a pale green.
	Paper	No visible change.

Table 5.20 Continued

Sample No.	*Ink Patch*	*Observations after light ageing under ambient light conditions*
3.5	Cyan	No visible change.
	Magenta	No visible change.
	Yellow	No visible change.
	Black	No visible change.
	Red	No visible change.
	Green	No visible change.
	Blue	Patch faded very slightly.
	25/50/75 % Cyan	No visible change.
	25/50/75 % Magenta	Patches faded slightly.
	25/50/75 % Yellow	No visible change.
	25/50/75 % Black	Patches faded, and change colour from a mid-grey to a orange/grey.
	25/50 % CMY	Patches faded, and changed colour from a mid-grey to a pale green.
	25/50 % CMYK	Patches faded, and changed colour slightly, from a mid-grey to a mid-green.
	Paper	No visible change.

Due to the limited space in the Perspex exposure box, the full range of colour patches were tested for the samples printed on Epson Presentation Matt paper (3.5), ISVE (3.2) and Somerset Velvet papers (3.3), and Whatman paper (3.4), and just the primary ink colours cyan, magenta, yellow and black were tested on the Epson Photo Glossy paper (3.1).

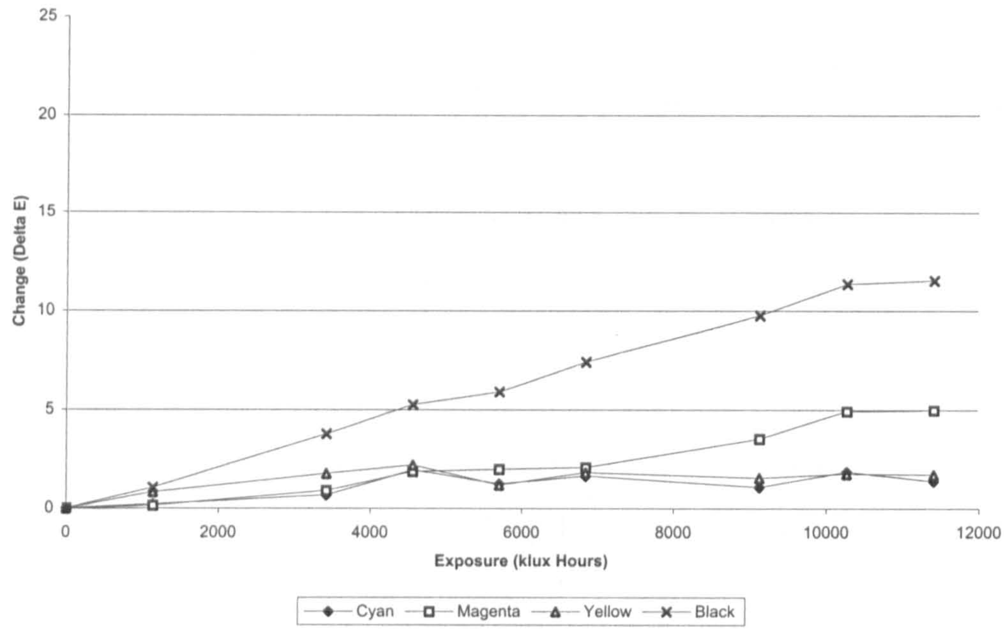

Fig. 5.30 Plot showing the change in ΔE_{ab} against exposure of the Epson Pro 9000 ink set printed on Inveresk Somerset Velvet paper (3.3) exposed to the fluorescent light fastness tester under an UV filter.

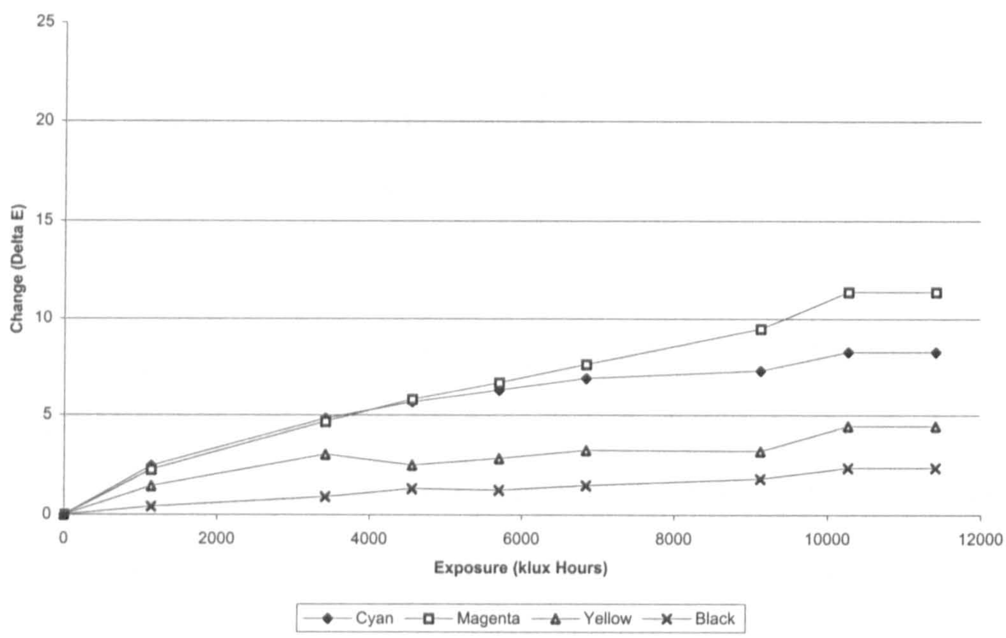

Fig. 5.31 Plot showing the change in ΔE_{ab} against exposure of the Epson Pro 9000 ink set printed on Somerset Velvet Enhanced (3.2) exposed to the fluorescent light fastness tester under an UV filter.

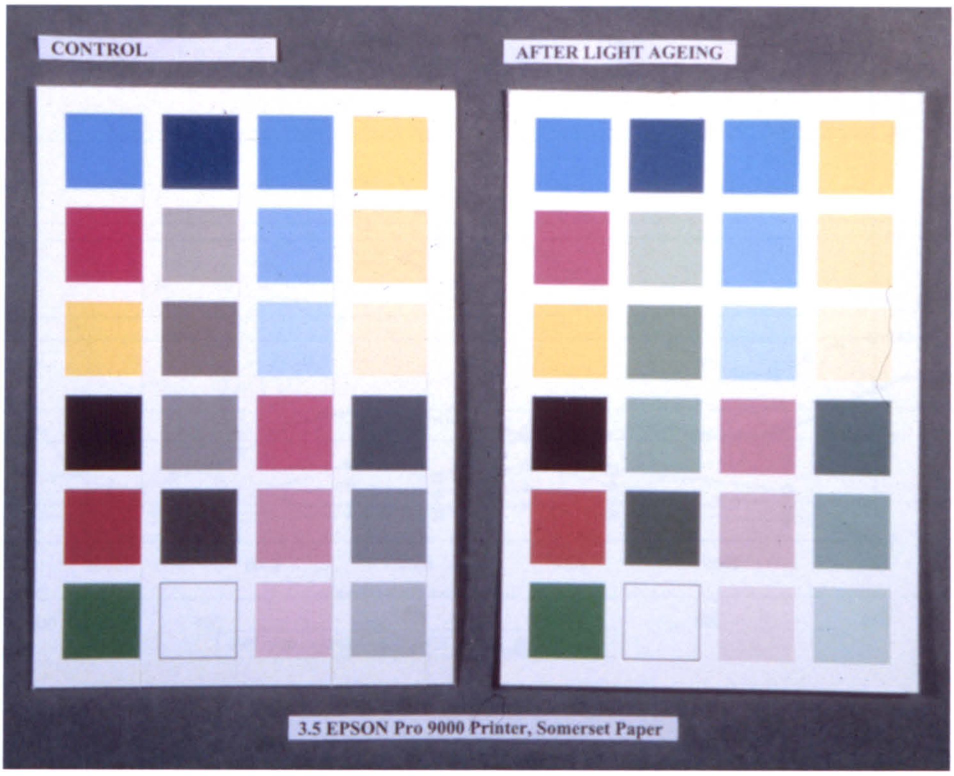

Fig. 5.32 Photograph of the Epson Pro 9000 print sample produced on Somerset Velvet paper (3.3). The left sample is the control and the right sample has been exposed to the fluorescent light tester with an UV filter.

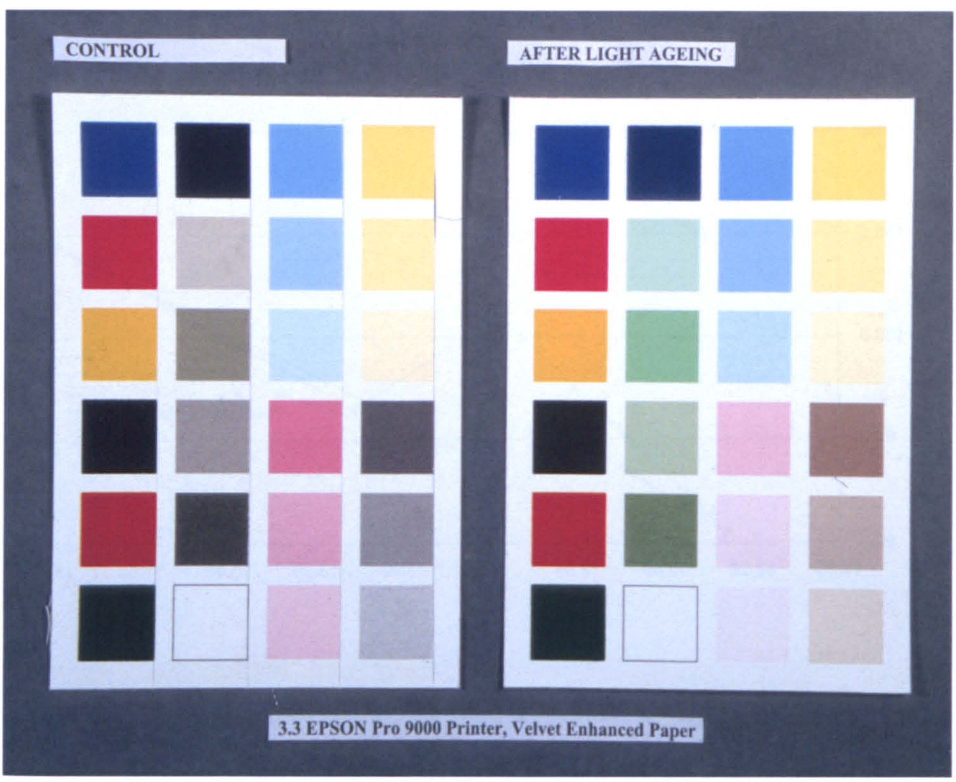

Fig. 5.33 Photograph of the Epson Pro 9000 print sample produced on ISVE paper (3.2) exposed to the fluorescent light fastness tester with a UV filter. The left sample is the control and the right sample has been exposed to the fluorescent light tester with an UV filter.

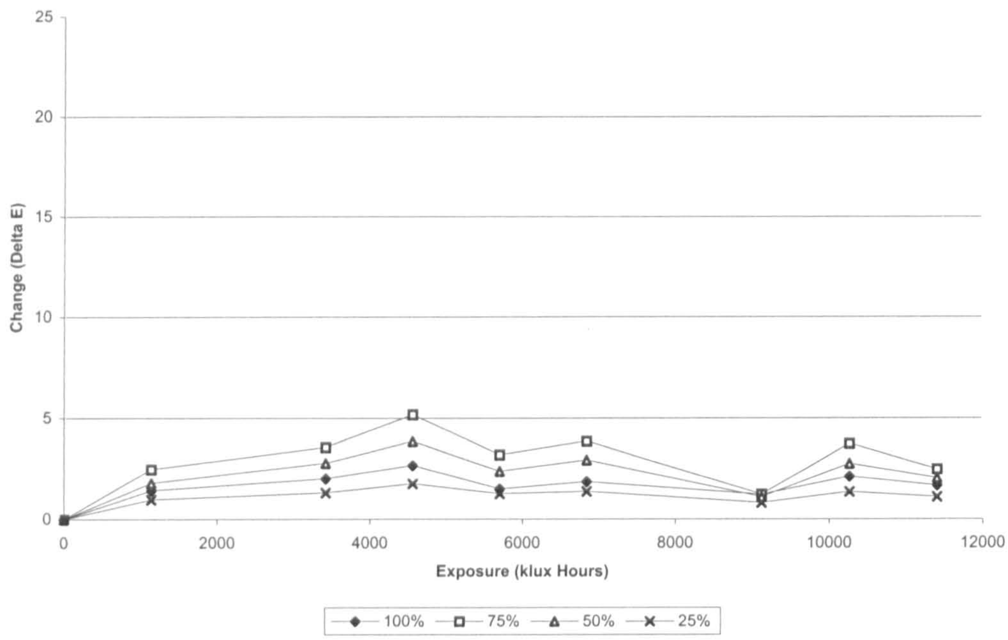

Fig. 5.34 Plot showing the change in ΔE_{ab} against exposure of the yellow ink from the Epson Pro 9000 ink set printed in different concentrations on the Epson Presentation Matt paper (3.5).

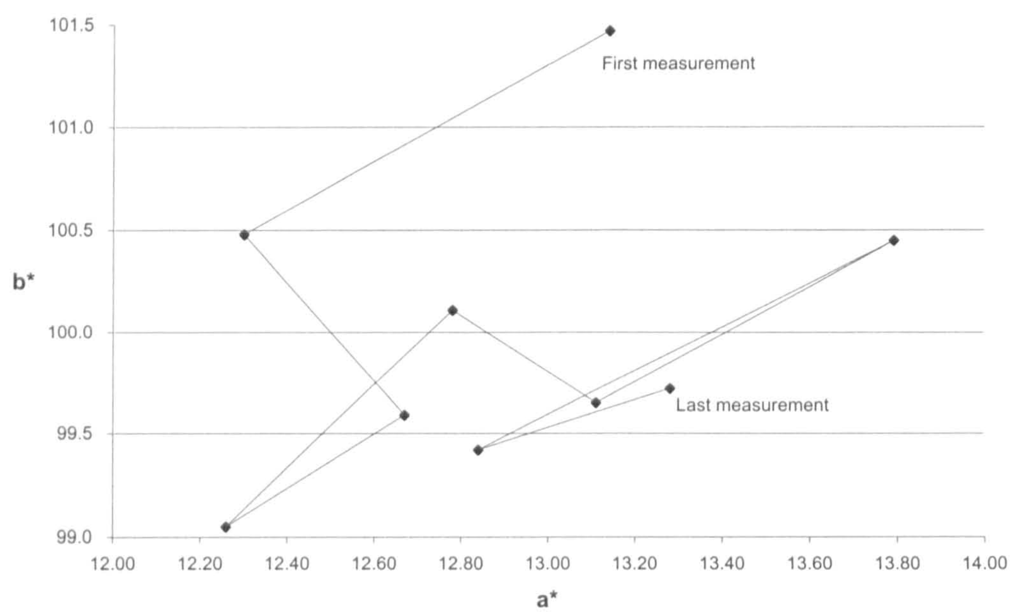

Fig. 5.35 Plot of the changes of redness (a*) and yellowness (b*) of the yellow ink from the Epson Pro 9000 ink set printed on Epson Presentation Matt.

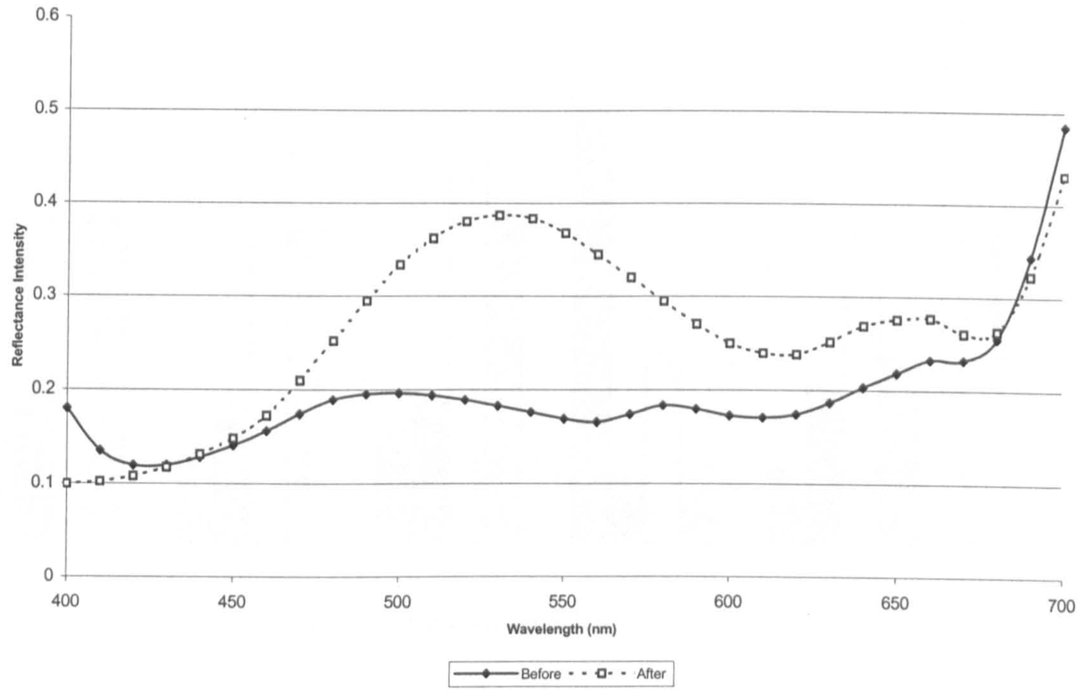

Fig. 5.36 Plot of change in the reflection spectra of the composite grey scale patch composed of 50 % cyan, magenta, yellow and black ink printed with the Epson Pro 9000 ink set on ISVE paper, after exposure to the fluorescent light tester with an UV filter.

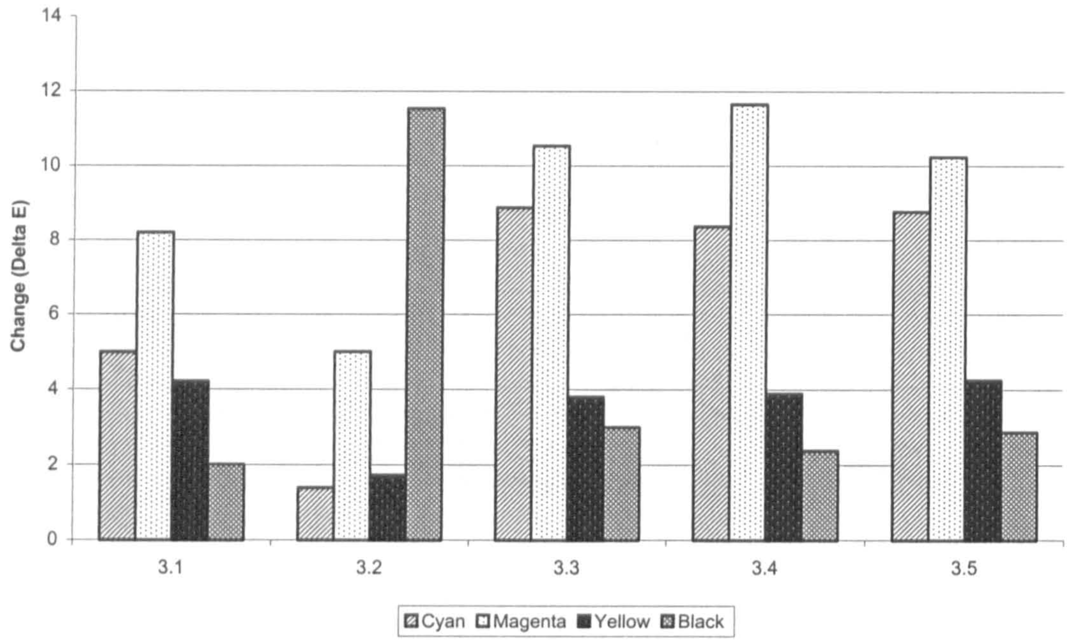

Fig. 5.37 Plot to show the change in ΔE_{ab} of the primary inks from the Epson Pro 9000 ink set printed on different substrates after exposure to the fluorescent light tester for 10 weeks or 8,521 klux hours with an UV filter.

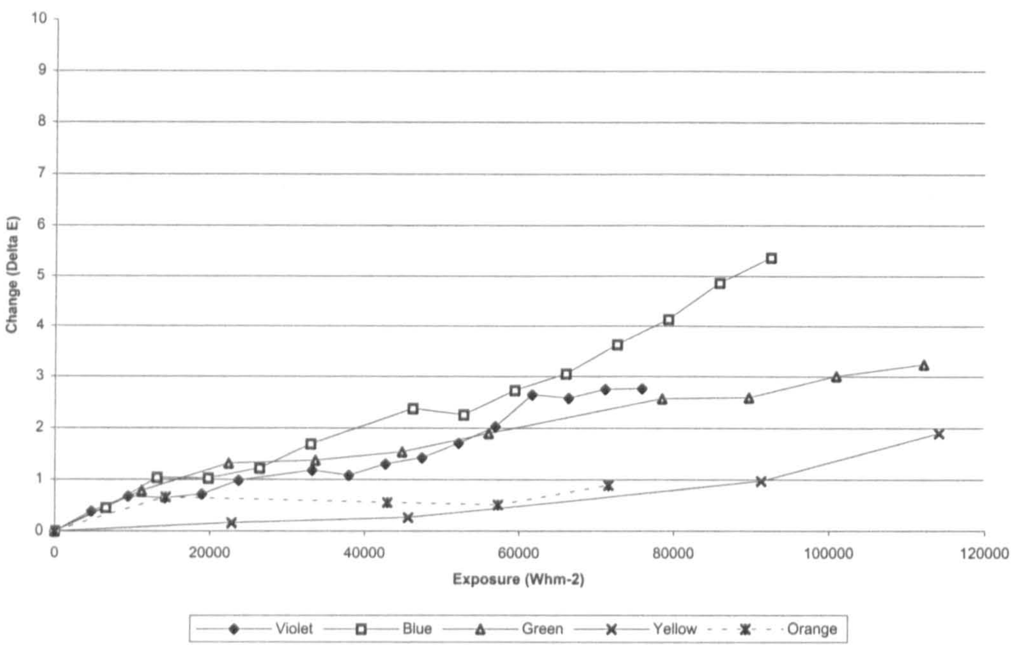

Fig. 5.38 Plot showing change in ΔE_{ab} against exposure for the black ink from the Epson Pro 9000 ink set printed on ISVE paper (3.2) exposed to the fluorescent light under the dichroic colour filters.

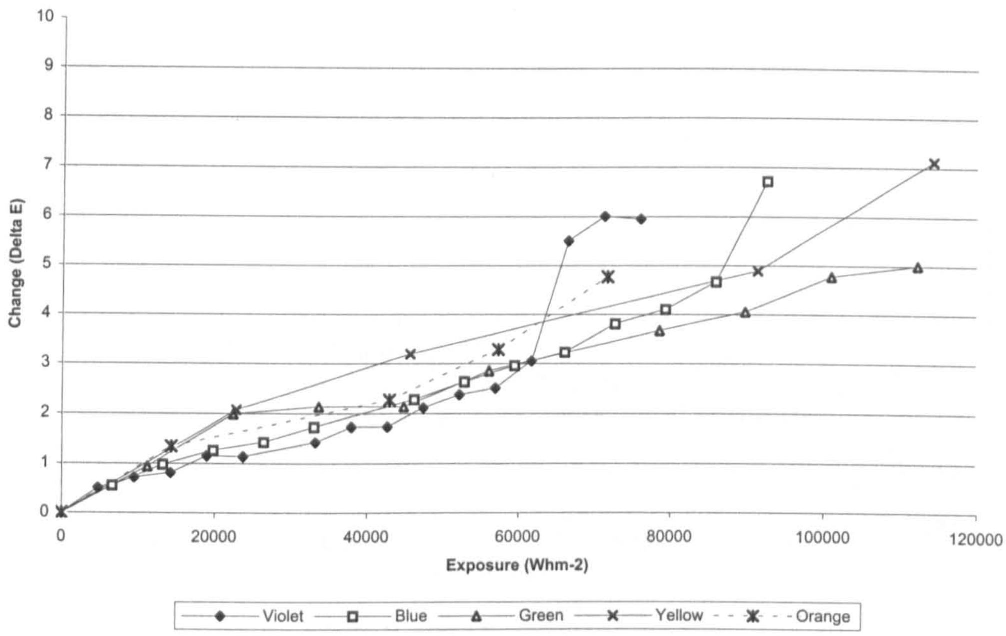

Fig. 5.39 Plot showing the change in ΔE_{ab} against exposure for the magenta ink from the Epson Pro 9000 ink set printed on Inveresk Somerset Velvet paper (3.3) exposed to fluorescent light under the dichroic filters.

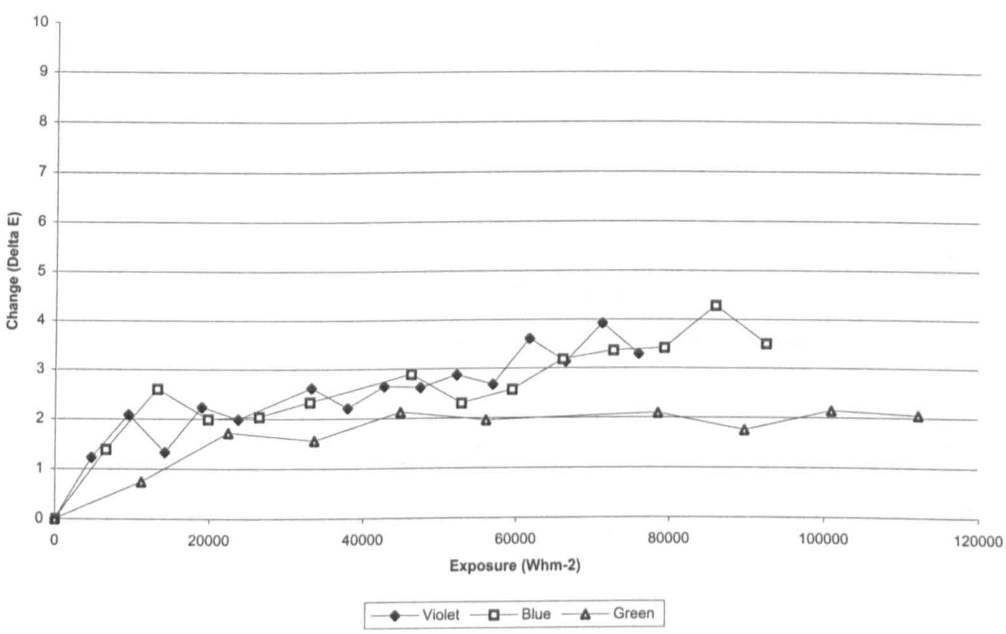

Fig. 5.40 Plot showing the change in ΔE_{ab} against exposure for the red ink patch from the Epson Pro 9000 ink set printed on ISVE paper (3.2), exposed to fluorescent light under the dichroic filters.

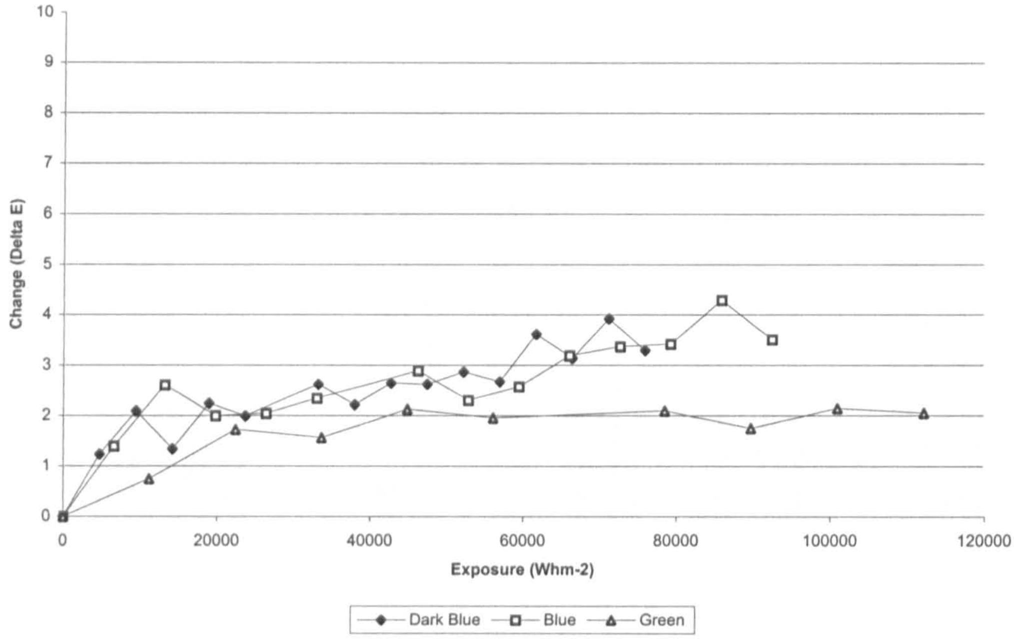

Fig. 5.41 Plot showing the change in ΔE_{ab} against exposure for the red ink patch from the Epson Pro 9000 ink set printed on ISVE paper (3.2), exposed to fluorescent light under the dichroic filters.

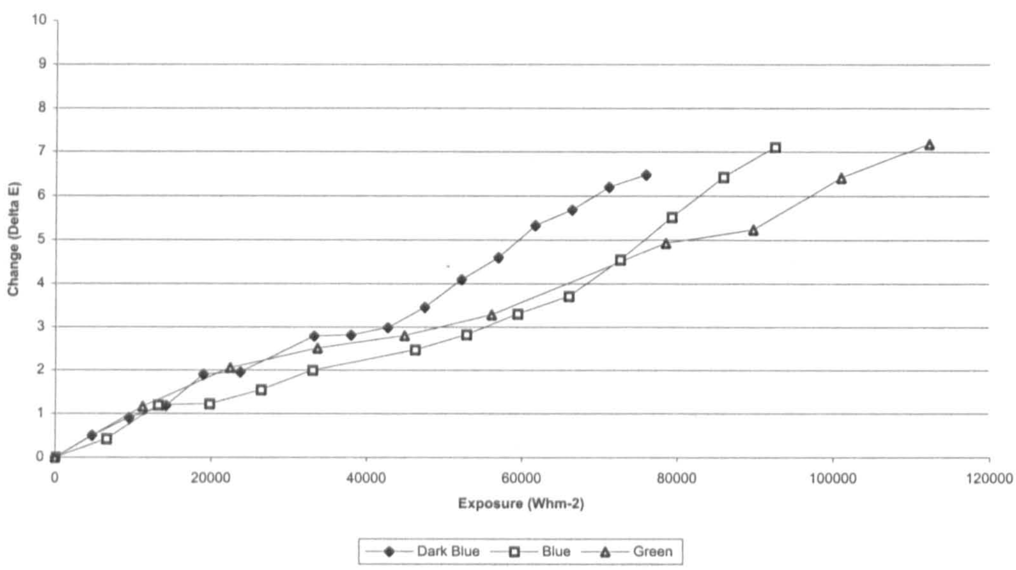

Fig. 5.42 Plot showing the change in ΔE_{ab} against exposure for the green ink patch from the Epson Pro 9000 ink set printed on ISVE paper (3.2), exposed to fluorescent light under the dichroic filters.

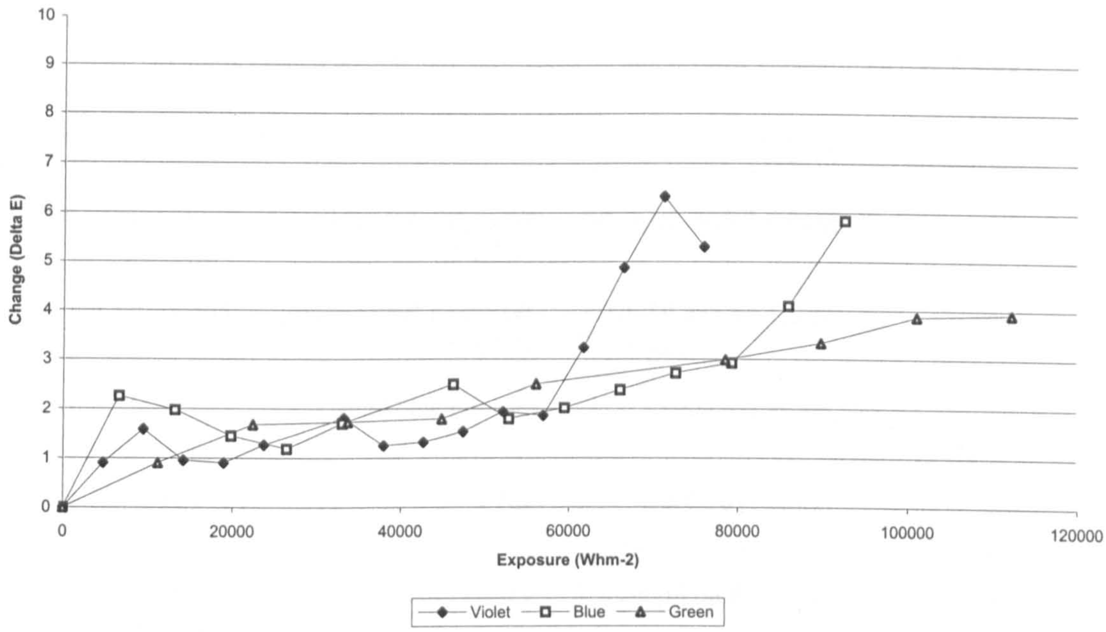

Fig. 5.43 Plot showing the change in ΔE_{ab} against exposure for the red ink patch from the Epson Pro 9000 ink set printed on Inveresk Somerset Velvet paper (3.3), exposed to fluorescent light under the dichroic filters.

5.6 PHOTOCHROMISM

Table 5.21 The following lists the samples that were found to be photochromatic.

Sample No	*Printer*	*Paper Type*	*Ink Type*
2.3	Mutoh Falcon RJ-4000	Whatman watercolour, 250 gsm	Lysonic cyan ink
2.4	Mutoh Falcon RJ-4000	Whatman Watercolour, 250 gsm	Fotonic cyan ink
3.1	Epson Pro 9000	Epson Photo Glossy	Pro 9000 yellow ink
3.2	Epson Pro 9000	ISVE	Pro 9000 yellow ink
3.6	Epson Photo Stylus 870	Epson Photo Glossy	Epson Photo Stylus cyan and yellow inks
4.1	Hewlett Packard 3500 DesignJet	Hewlett Packard Heavy weight coated paper	3500 Design Jet yellow ink

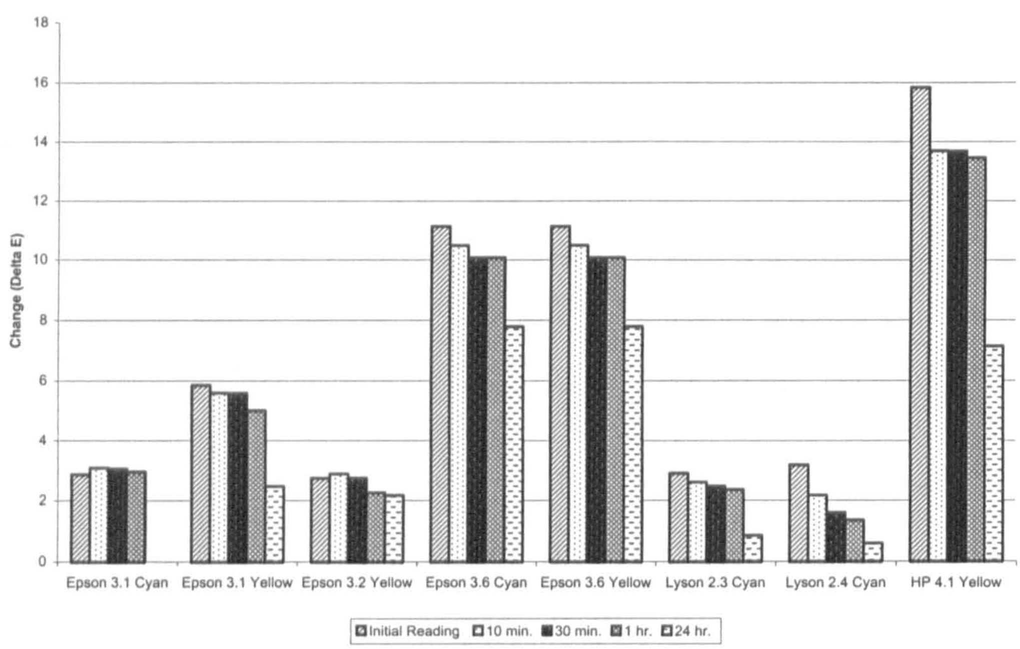

Fig. 5.44 Bar chart of the change in ΔE_{ab} over time after the samples were removed from the Microscal Light Fastness Tester and placed in dark storage.

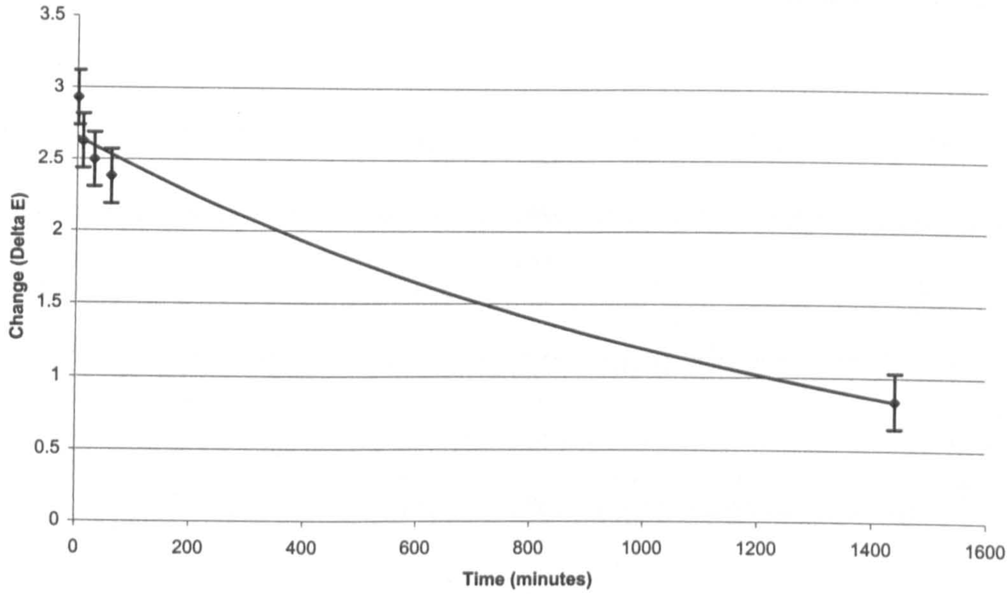

Fig. 5.45 Plot showing the change in ΔE_{ab} against time of the cyan ink from the Lysonic ink set printed on Whatman watercolour paper (2.3), after the sample was removed from the Microscal Light Fastness Tester (including standard deviation results).

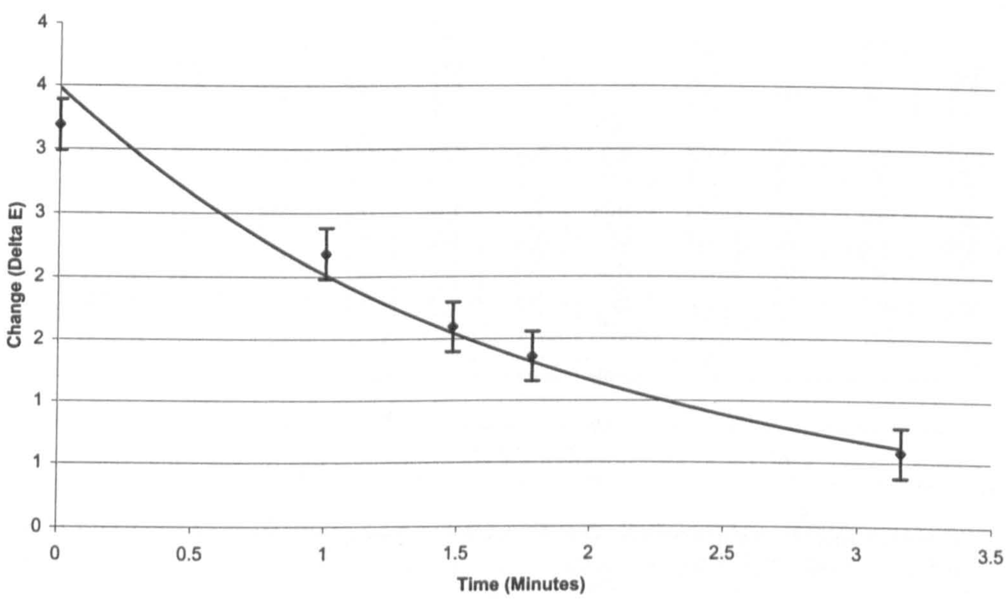

Fig. 5.46 Plot showing the change in ΔE_{ab} against time of the cyan ink from the Fotonic ink set printed on Whatman watercolour paper (2.4), after the sample was removed from the Microscal Light Fastness Tester (including standard deviation results).

5.7 COLOUR GAMUT GRAPHS

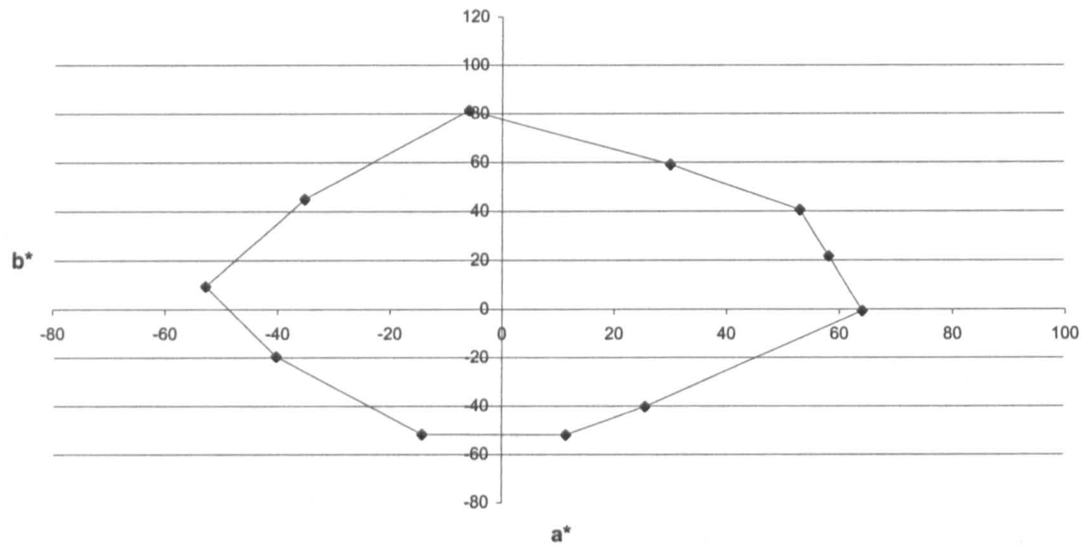

Fig. 5.47 Plot showing the colour gamut of the Lysonic ink printed on Lyson Soft Fine Art paper (2.1).

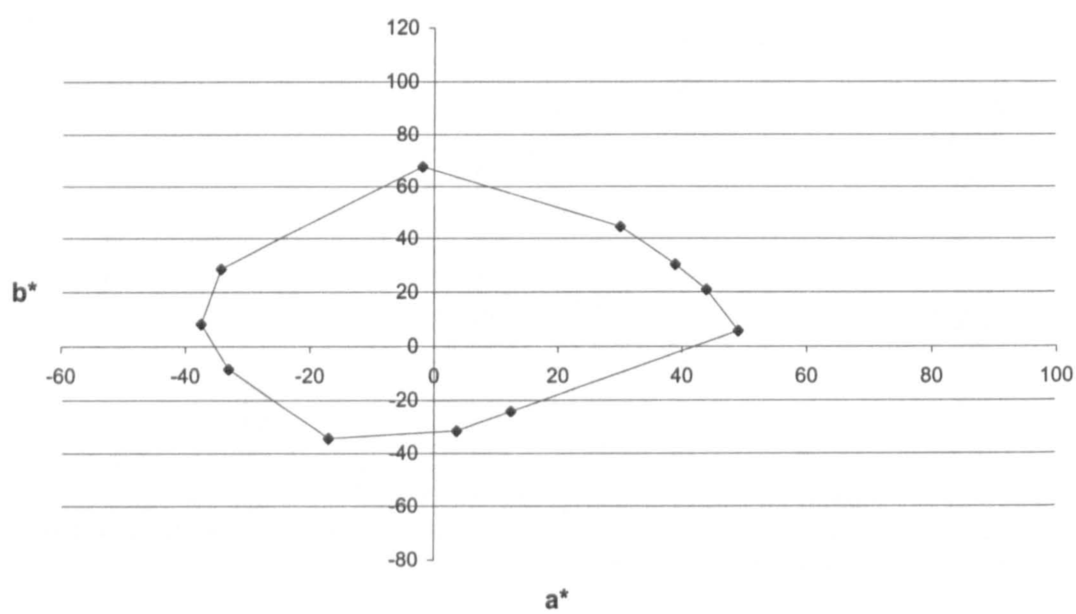

Fig. 5.48 Plot showing the colour gamut of the Lysonic ink printed on Whatman watercolour paper (2.3).

5.8 THERMAL AGEING OF PAPERS

5.8.1 Visual examination

All of the samples showed some degree of discolouration after thermal ageing. The uncoated Inveresk Somerset Velvet paper had hardly changed on ageing and looked slightly grey compared to the control. The Whatman paper and ISVE papers had discoloured turning slightly yellow. All of the other coated ink jet and electrophotographic papers had all yellowed significantly, with the coated side of the ink jet papers showing further discolouration than the uncoated verso.

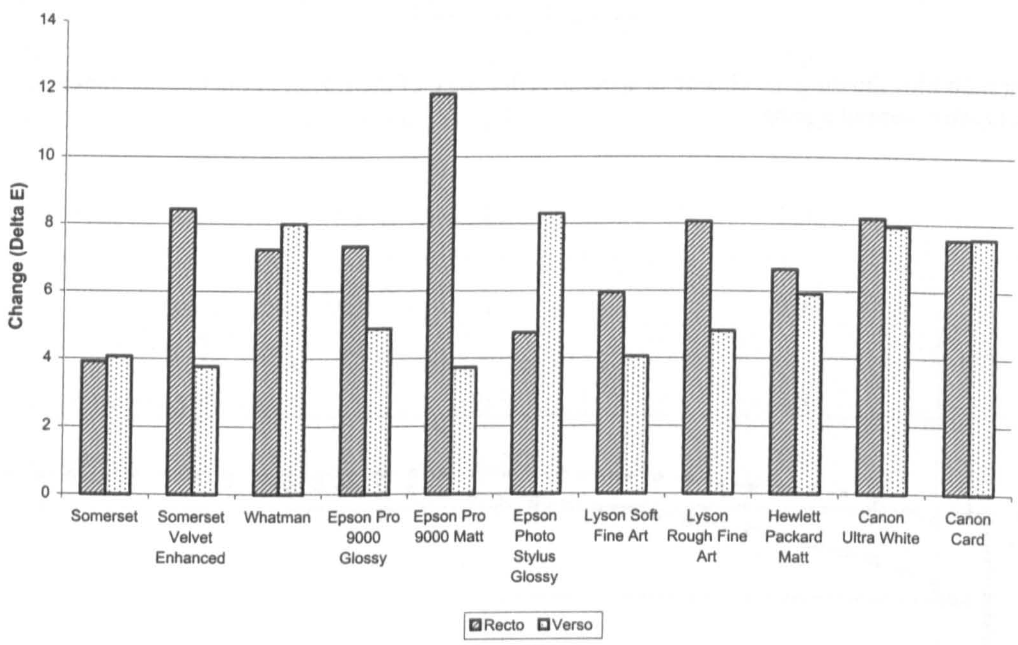

Fig. 5.49 Bar chart showing change in ΔE_{ab} of the ink jet and electrophotographic papers after thermal ageing for three weeks. Thermal ageing conditions were set at 80 °C and 60 % RH.

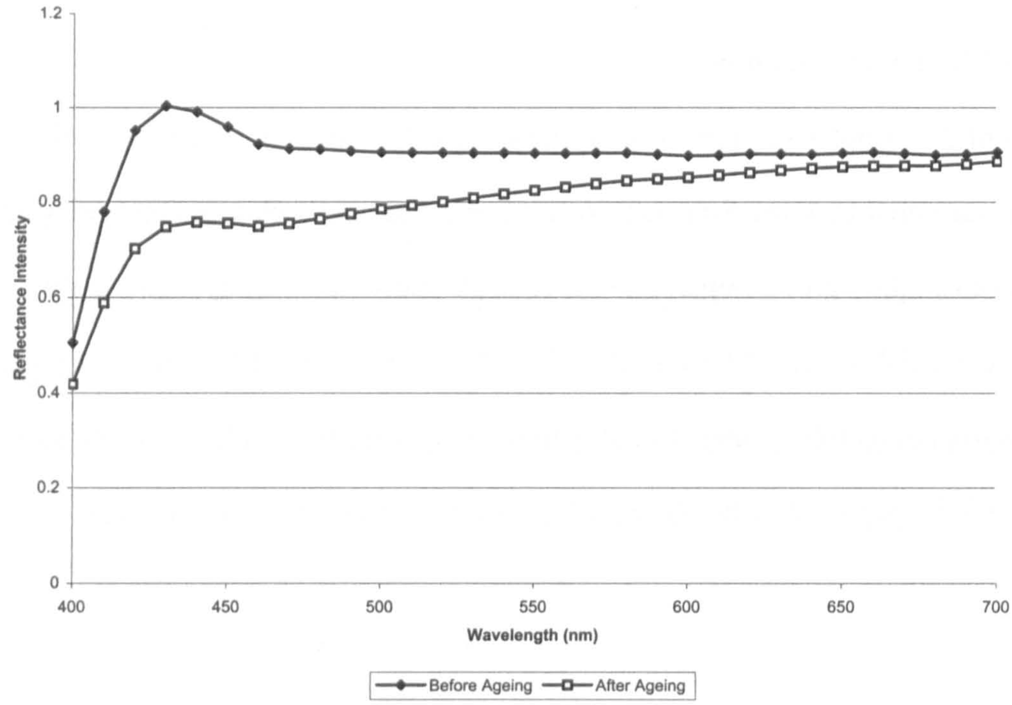

Fig 5.50 Plot showing the change in spectral reflectance of the Epson Photo Glossy Paper (Recto) (3.1) after thermal ageing.

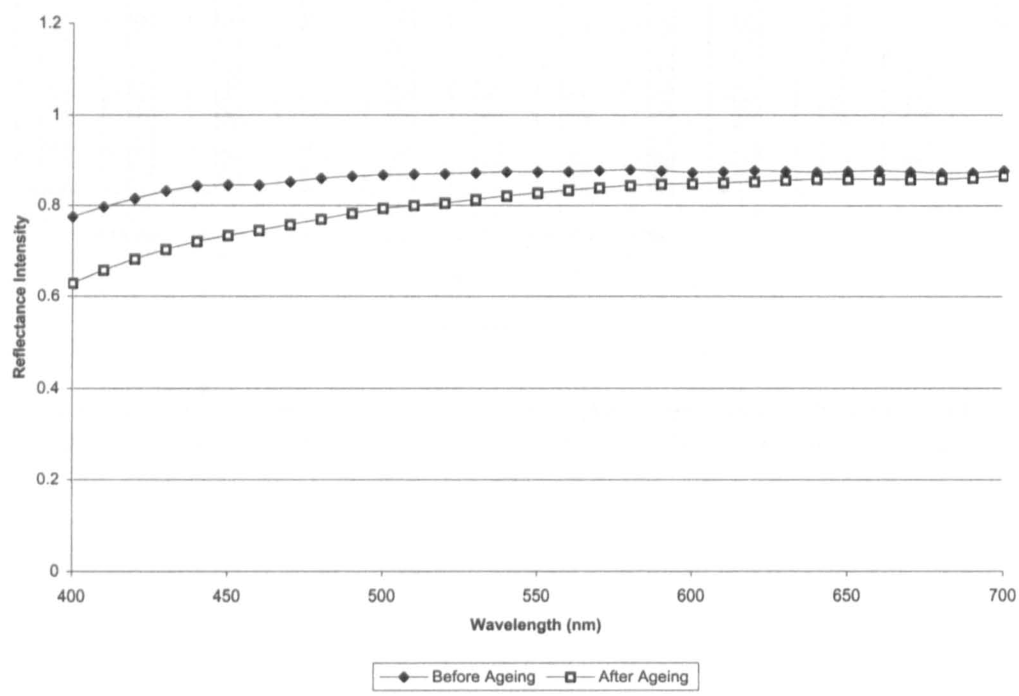

Fig 5.51 Plot showing the change in spectral reflectance of the Epson Photo Glossy Paper (Verso) (3.1) after thermal ageing.

5.8.2 pH values of the ink jet and electrophotographic papers by cold extraction

Table 5.22 Average pH value of the papers tested in this investigation before and after thermal ageing, obtained by cold extraction.

Paper	*pH of Paper Before Thermal Ageing*	*pH of Paper After Thermal Ageing*
Somerset Velvet, Radiant White, 280 gsm (Inveresk)	8.1	7.0
Watercolour, 250 gsm (Whatman)	8.3	6.2
Soft Fine Art Watercolour, 285 gsm (Lyson)	7.6	7.3
Rough Fine Art Watercolour, 210 gsm (Lyson)	7.6	7.1
Photo Glossy, 190 gsm (Epson Pro 9000)	5.2	5.3
ISVE, 225 gsm (Inveresk)	8.5	7.0
Presentation Matt, 172 gsm (Epson Pro 9000)	7.8	7.4
Photo Glossy, 141 gsm (Epson Photo Stylus)	5.2	5.9
Heavy Weight Coated Paper – Matt, 130 gsm (Hewlett Packard)	6.4	5.9
Ultra White, 105 gsm (Canon)	6.3	5.8
Card, 209 gsm (Canon)	6.4	5.9

5.8.3 Test for the effect of stacking in storage

Only the Canon print samples were affected by the test, all of the ink jet samples remained unchanged. The toner from the Canon samples had adhered to the paper laid on top of the sample, but was easily peeled from the above sheet leaving some of the colorant on the covering paper. All the toner colorants were affected, but the magenta and black toners showed the most sensitivity to transfer in stacking.

5.9 CONSERVATION TESTING

5.9.1 Mechanical dry cleaning

Table 5.23 Visual observations recorded under ambient light and magnification (X 10) after various mechanical dry cleaning methods were tested on the print materials.

Sample No.	*Draft Cleaning Powder*	*Latex Sponge*	*Grated Plastic Eraser*	*Pad*
1.1	No change	Colour removed	Colour removed	Surface marks on colorant
1.2	No change	Colour removed	Colour removed	Surface marks on colorant
2.1	No change	No change	Colour removed	Surface marks on colorant
2.2	No change	No change	Colour removed	Colour removed
2.3	No change	Colour removed	Surface marks on colorant	Colour removed
2.4	No change	Colour removed	Surface marks on colorant	Colour removed
3.1	No change	Surface marks on colorant	Surface marks on colorant	No change
3.2	Colour removed	Colour removed	Colour removed	Surface marks on colorant
3.3	No change	Colour removed	Colour removed	No change
3.4	No change	No change	Surface marks on colorant	No change
3.5	No change	Surface marks on colorant	Surface marks on colorant	No change
3.6	Surface marks on colorant	Surface marks on colorant	Surface marks on colorant	No change
4.1	No change	Colour removed	Surface marks on colorant	Surface marks on colorant
5.1	No change	Surface marks on colorant	Surface marks on colorant	No change
5.2	Surface marks on colorant	Colour removed	Surface marks on colorant	No change
5.3	No change	Surface marks on colorant	Surface marks on colorant	No change

Table 5.23 Continued

Sample No.	*Draft Cleaning Powder*	*Latex Sponge*	*Grated Plastic Eraser*	*Pad*
5.4	No change	No change	Surface marks on colorant	No change
5.5	No change	No change	Surface marks on colorant	No change

The mechanical dry cleaning treatments did not show any signs of damage to the surface of the papers tested.

5.9.2 Humidification

No visual differences could be seen under ambient light and magnification (X 20), after the print samples were humidified for four hours. However, examination of the ΔE_{ab} results show that the treatment did affect the samples, especially the prints identified as sensitive to washing treatments (see 5.9.3).

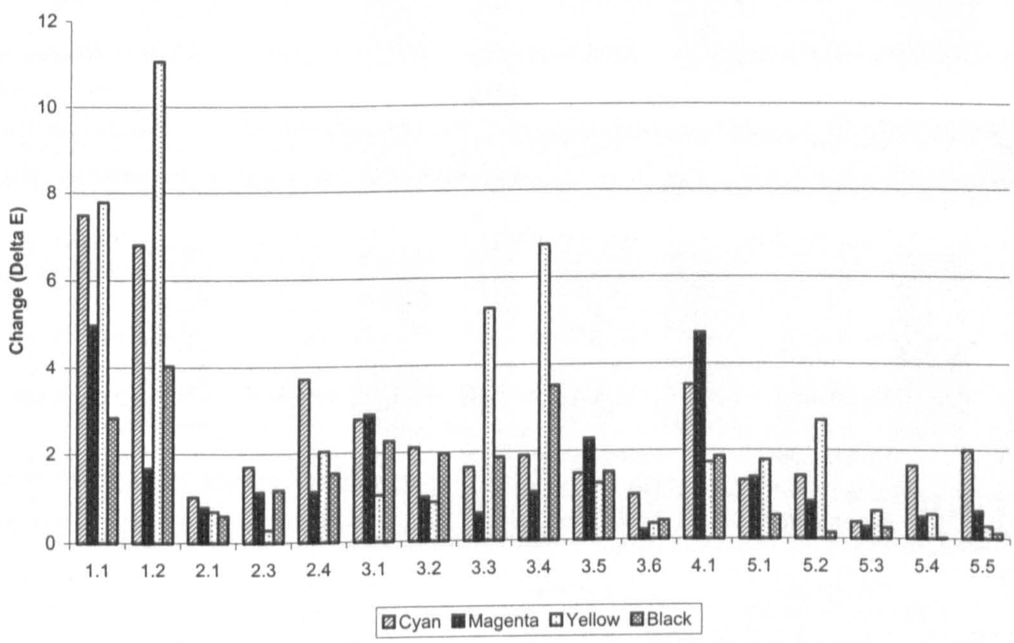

Fig. 5.52 Bar chart showing the change in ΔE_{ab} of the print materials after humidification for four hours.

5.9.3 Washing

Table 5.24 Visual observations recorded under ambient light and magnification (X 10) after subjecting the print material to various washing treatments.

Sample No.	*Spot Test*	*Submersion in Water Bath (5 min.)*	*Submersion on Water Bath (15 min.)*	*Drying pressed between blotting paper*
1.1	All inks very fugitive	N/a	N/a	N/a
1.2	All inks very fugitive	N/a	N/a	N/a
2.1	No change	No change	No change	No change
2.2	No change	Black slightly fugitive	Black slightly fugitive	Black displaced on blotting paper
2.3	All inks very fugitive	N/a	N/a	N/a
2.4	All inks very fugitive	N/a	N/a	N/a
3.1	Water stain after drying on all inks	Black slightly fugitive	Black slightly fugitive	Black displaced on blotting paper
3.2	All inks very fugitive	N/a	N/a	N/a
3.3	All inks fugitive	N/a	N/a	N/a
3.4	All inks fugitive	N/a	N/a	N/a
3.5	Paper cockled	Black fugitive	Black fugitive	Black displaced on blotting paper
3.6	No change	Black fugitive	Black fugitive	Black displaced on blotting paper
4.1	Black slightly fugitive	Black slightly fugitive	Black fugitive	Black displaced on blotting paper
5.1	No change	No change	No change	No change
5.2	No change	No change	No change	No change
5.3	No change	No change	No change	No change
5.4	No change	No change	No change	No change
5.5	No change	No change	No change	No change

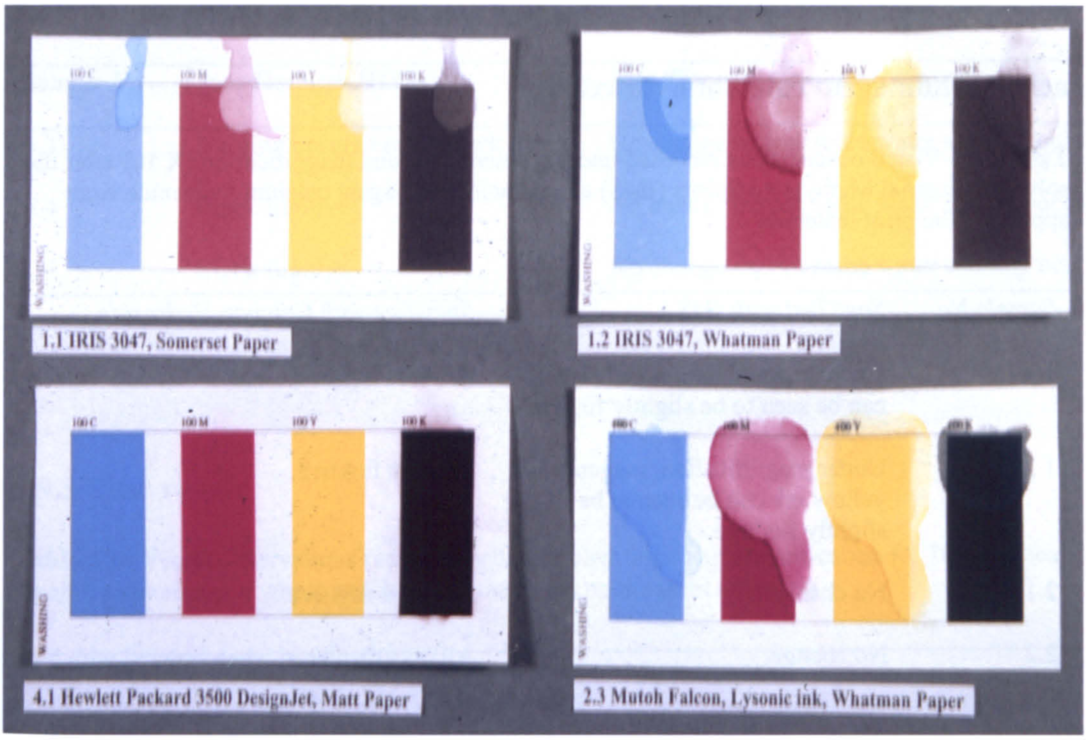

Fig. 5.53 Photograph of Iris print samples printed on Somerset Velvet (1.1) and Whatman watercolour (1.2) papers, Hewlett Packard print sample (4.1) and Lysonic print sample produced on Whatman watercolour paper (2.3) after one droplet of water was applied.

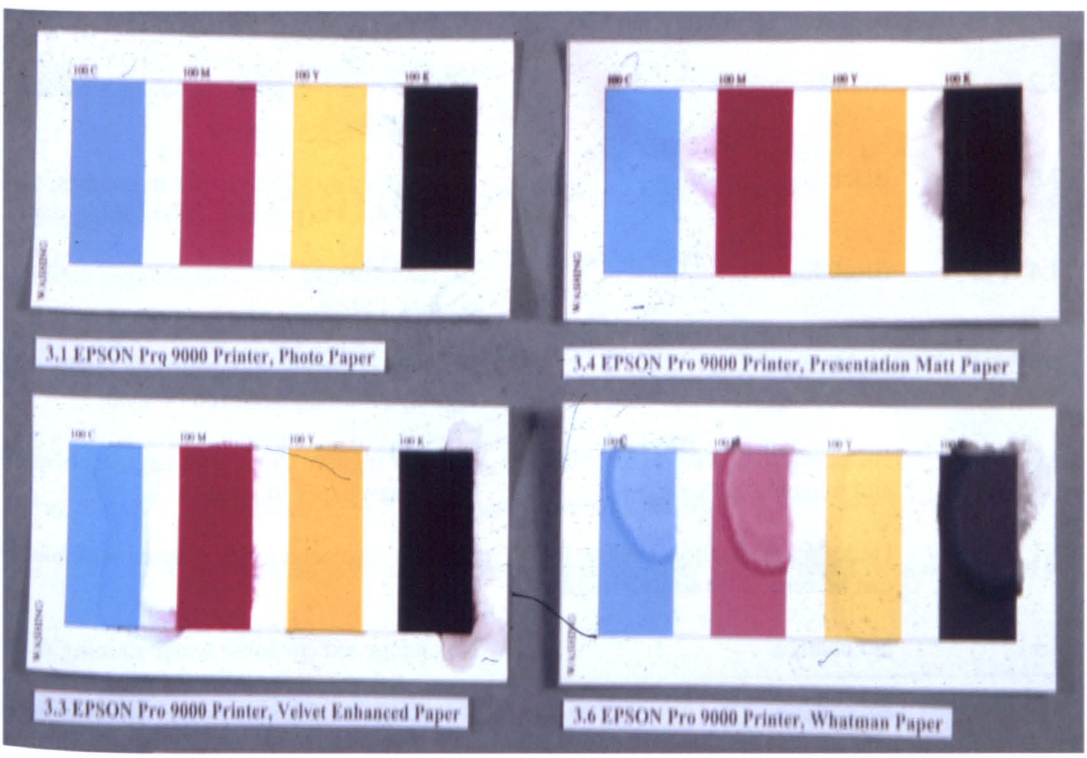

Fig. 5.54 Photograph of Epson Pro 9000 print samples printed on Photo Glossy (3.1), ISVE (3.2), Presentation Matt (3.5) and Whatman watercolour (3.4) papers after one droplet of water was applied.

5.9.4 Application of industrial methylated spirits (IMS) and the de-acidification agent calcium hydroxide

Table 5.25 Visual observations recorded under ambient light and magnification (X 10) after the solvent Industrial Methylated Spirits (IMS) and de-acidifying agent calcium hydroxide were applied to the print materials.

Sample No.	*Spot Test with IMS*	*Spot Test with Calcium Hydroxide*
1.1	Under magnification, yellow ink can be seen to be slightly fugitive.	All inks fugitive.
1.2	Under magnification, magenta and yellow ink can be seen to be slightly fugitive.	All inks fugitive.
2.1	No change.	Magenta fugitive.
2.2	No change.	All inks displaced when pressed with blotting paper.
2.3	Black fugitive.	All inks fugitive.
2.4	Magenta and black very slightly fugitive.	All inks fugitive.
3.1	Under magnification, black ink can be seen to be slightly fugitive.	Magenta changed colour turning orange. Black fugitive, staining occurred on cyan.
3.2	All inks fugitive	All inks fugitive, magenta changes colour turning orange.
3.3	Black slightly fugitive.	Black lifts away from paper in patches, all inks displaced when pressed with blotting paper.
3.4	Black fugitive.	All inks fugitive, magenta changes colour turning orange.
3.5	No change.	Magenta changed colour turning orange. Black fugitive, staining occurred on cyan.
3.6	Black fugitive, staining on cyan and magenta ink patches.	All inks fugitive to varying degrees, black lifts away from paper in patches.
4.1	Under magnification, yellow ink can be seen to be slightly fugitive.	All inks displaced when pressed with blotting paper.
5.1	No change.	No change except some water staining occurred
5.2	No change.	No change except some water staining occurred

Table 5.25 Continued

Sample No.	*Spot Test with IMS*	*Spot Test with Calcium Hydroxide*
5.3	Staining occurs on the black patch	No change except some water staining occurred
5.4	Black fugitive	No change except some water staining occurred
5.5	Black fugitive	No change except some water staining occurred

5.9.5 Tear repair

Table 5.26 Visual observations recorded under ambient light and magnification (X 10) after tear repair treatment using wheat starch paste was tested on the print materials.

Sample No.	*Observation under ambient light after tear repair*
1.1	Magenta, yellow and black ink fugitive with paste.
1.2	Magenta, yellow and black ink fugitive with paste.
2.1	No change to ink. Paper does not adhere very well.
2.2	No change to ink. Paper does not adhere very well.
2.3	Black fugitive with paste.
2.4	Black fugitive with paste.
3.1	No change to ink, but paste stains the paper.
3.2	No change to ink, but paste stains the paper.
3.3	No change.
3.4	No change.
3.5	No change to ink, but paste stains the paper.
3.6	No change to ink, but paste stains the paper.
4.1	No change to ink, but paste stains the paper and the paper does not adhere well.
5.1	No change.

Table 5.26 Continued

Sample No.	*Observation under ambient light after tear repair*
5.2	No change.
5.3	No change.
5.4	No change.
5.5	No change.

5.10 IDENTIFICATION

5.10.1 Visual examination under ambient light

All of the ink jet inks printed on the uncoated Inveresk Somerset Velvet and Whatman watercolour papers had a soft subdued appearance. The magenta ink from all of the ink sets appears less vibrant on the uncoated papers. The Epson and Lyson magenta inks also looks bluer in tone. The black ink from all the ink sets appears less dense, becoming a dark grey tone.

All of the Epson Pro 9000 inks printed on the coated ISVE paper, which looks and feels like an uncoated paper but has a coating for ink jet inks, are much brighter and more vivid in tone. This is more obvious when the printed sample is placed next to a sample printed on one of the uncoated papers.

The printed side of the ink jet coated papers are often very bright white, although the degree of brightness varies for different coated papers. Gloss coatings are easier to identify than matt surfaces as they reflect much light and are smooth to the touch. The Epson Photo Stylus 870 Photo Glossy paper is very smooth on both sides of the sheet, which could be an indication of a plastic base. Ink jet coated more difficult to identify because they look and feel like regular bond paper. Printing on matt-coated papers appears very clear with regular dots, the ink colours remain vivid, and there is little or no physical dot gain.

Ink jet printing can sometimes be identified with certain printing systems as the dots are visible to the naked eye in the lightly printed areas of 50 % or lower. The ink jet nozzles on the printer are very fine and can often be blocked at the time of printing causing fine unprinted lines to run across solid areas of colour. This effect is a recognised occurrence for ink jet prints and has been termed banding. Evidence of banding could be seen on the Epson Pro 9000 sample printed on Photo Glossy paper.

Fig. 5.55 Photograph of the 'banding' that occurred on the cyan ink patch from the Epson Pro 9000 sample printed on Photo Glossy paper (3.1).

The Canon printed patches were all very solid in appearance and the toner appeared to form a plastic layer on the surface of the paper, which reflected more light and had a slightly glossy appearance. Fine yellow sporadic printed dots could be seen to cover the Canon Ultra White and Canon Card substrates.

5.10.2 Visual observations under transmitted light

Plastic base and fibre-based material can easily be identified with the aid of transmitted light. Paper fibres can clearly be seen, but with a plastic based sheet the substrate appears very even - this was seen with the Epson Photo Stylus 970 Photo Glossy paper. The coated ISVE paper is less transparent than uncoated Inveresk Somerset paper.

5.10.3 Visual observation under raking light

The glossy papers supported by a paper base looked slightly uneven in raking light as the covering layer followed the irregular surface of the paper underneath. The Epson Photo Stylus 870 Photo Glossy paper had a completely flat surface. All of the surfaces on the matt-coated papers looked very porous under raking light, as tiny holes or troughs could be easily seen.

5.10.4 Visual observation under ultra violet radiation

All of the gloss and matt-coated papers fluoresced bright white under this form of radiation except for the Epson Photo Stylus 870 Photo Glossy paper. The Canon Ultra White paper and Card and the Lyson coated fine art papers also fluoresced bright white. The coated ISVE paper and the uncoated Inveresk Somerset Velvet and Whatman watercolour papers did not show any sign of fluorescence.

5.10.5 Microscopic examination

Under magnification (X 10), the composing dots could be seen on all of the ink jet prints. These dots were less obvious on the Iris ink jet samples and could only be seen on the lightly printed areas of 35 % or less. The dots on the Iris prints are of varying sizes. On the Epson Pro 9000 ink jet prints all the dots looked the same size. The Epson Pro 9000 samples produced with one colour (C, M or Y) at 100 % concentration were not composed of pure colour. Instead, fine dots of the primary printing colours were printed with the 100 % printed patch, e.g. the 100 % M patch contained fine dots of the cyan and yellow ink (see fig. 5.56).

Fig. 5.56 Photograph of the 100 % magenta ink patch from the Epson Pro 9000 ink set printed on Somerset Velvet paper.

The lateral movement of the ink jet print head as it lays down the ink can also be seen under magnification. On the uncoated papers the ink jet ink can be seen to wick along the paper fibres, and lines have poor edge definition.

On the Epson Photo Stylus sample the printed black is made up of cyan, magenta, yellow and black inks laid on top of one another. This can be seen on the edges of the patches of black ink printed in concentrations of 100 %, 75 %, 50 % and 25 %, and on the black lines. The black ink patches produced from the Epson Pro 9000 and Hewlett Packard 3500 samples are also made up of this print combination, but lines and text are made of the black ink only. On the Iris print samples the ink patches printed in individual concentrations are composed of just the ink colour specified in the computer software programme. On the Lyson samples printed on the Lyson coated papers, the dots composing the 100 % cyan ink printed patch could be clearly seen under magnification and ambient light, whereas the magenta, yellow and black 100 % printed patches show a continuously printed block of colour. All the primary ink colours patches are composed of the individual colours only. The dots are irregular in size on the coated papers and seem to follow the uneven surface of the paper, but there is no wicking present. Wicking has occurred with the Lysonic and Fotonic inks printed on the uncoated Whatman watercolour paper.

Examination of the ink jet papers under X 20 magnification revealed that the Epson Pro 9000 Photo Glossy paper can be seen to be composed of two layers at the corners of the sheet. The top coating has a very smooth edge but fibres can be seen to project from the edge of the base paper underneath. The coated side of the paper also looks very different to the verso. The coating has a very smooth even surface with no paper fibres visible, but on the back of the sheet only paper fibres are visible.

The Epson Presentation Matt coated paper also appears to be made up of two layers, visible under X 10 magnification. Observations at the corner edge of the sheet show the coating layer can be clearly seen and there are paper fibres projecting from the base underneath.

On the ISVE paper the voids that normally occur on a paper surface are less obvious on one side of the paper (specified as the printing side on the packaging) than the other the side. However, no obvious coating is visible even at the edges of the paper.

Examination of the Epson Photo Stylus 870 Photo Glossy paper under magnification at the edges of the sheet shows that the paper appears to be composed of three layers with a coating of the top, a paper layer sandwiched in the middle and a plastic type base. At the corners of the sheet the edges are very straight with no paper fibres protruding.

On the Canon samples the patches could be seen to be composed of lines that either ran across the length of the sheet (for the Canon 1150 laser printer and the CLC 900 laser printer) (see fig. 5.57) or diagonally (for the CLBP 460 PS laser printer) (see fig. 5.58). For patches specified in the computer software to be made up of two of more ink colours, these lines were clearly seen under magnification very clear and sharp. The toner colorants could be seen to coat the paper forming a uniform coverage. The yellow printed dots visible under ambient light on the Canon Ultra White and Card substrates could be clearly seen.

Fig. 5.57 Photograph of the orange patch from the Canon 1150 laser printer printed on Canon Ultra White paper (5.1).

Fig. 5.58 Photograph of the orange printed patch from the Canon CLBP 460 PS laser printer printed on Canon Ultra White paper (5.4).

5.11 CHEMICAL SPOT TESTS

The chemical spot test for the presence of azo dyes was not successful, because the quantity of dye available on the paper was not enough to enable detection.

Table 5.27 Results recorded after various chemical spot tests were applied to the various papers and printed materials investigated

Paper	*Presence of Lignin*	*Presence of Mechanical Wood Pulp*	*Presence of Starch*	*Presence of Gelatine*
Somerset	No	No	Yes	Yes
Somerset Velvet Enhanced	No	No	Yes	Yes
Whatman	No	No	Yes	Yes
Epson Pro 9000 Photo Glossy	No	No	Yes (paper only)	No
Epson Pro 9000 Presentation Matt	No	No	Yes	No
Epson Photo Stylus Glossy	No	No	Yes	No
Lyson Soft Fine Art	No	No	Yes (paper only)	Yes
Lyson Rough Fine Art	No	No	Yes (paper only)	Yes
Hewlett Packard Matt	No	No	Yes (paper only)	Yes
Canon Ultra White	Yes	Yes	Yes	No
Canon Card	Yes	Yes	Yes	No

5.12 CHROMOTOGRAPHY

Only the black inks from the Lyson, Epson and Hewlett Packard diffused with the thin layer chromatography paper. All of these inks showed to be composed of a pale orange and a purple colorant.

5.13 SCANNING ELECTRON MICROSCOPY

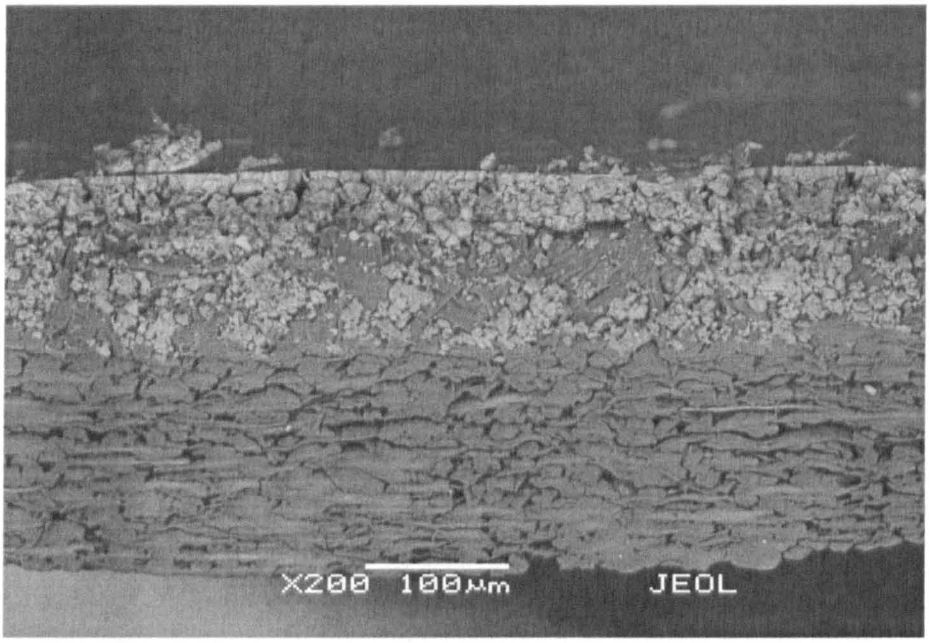

Fig. 5.59 SEM photograph of the cross-section of the Epson Photo Glossy paper (3.1) X 200.

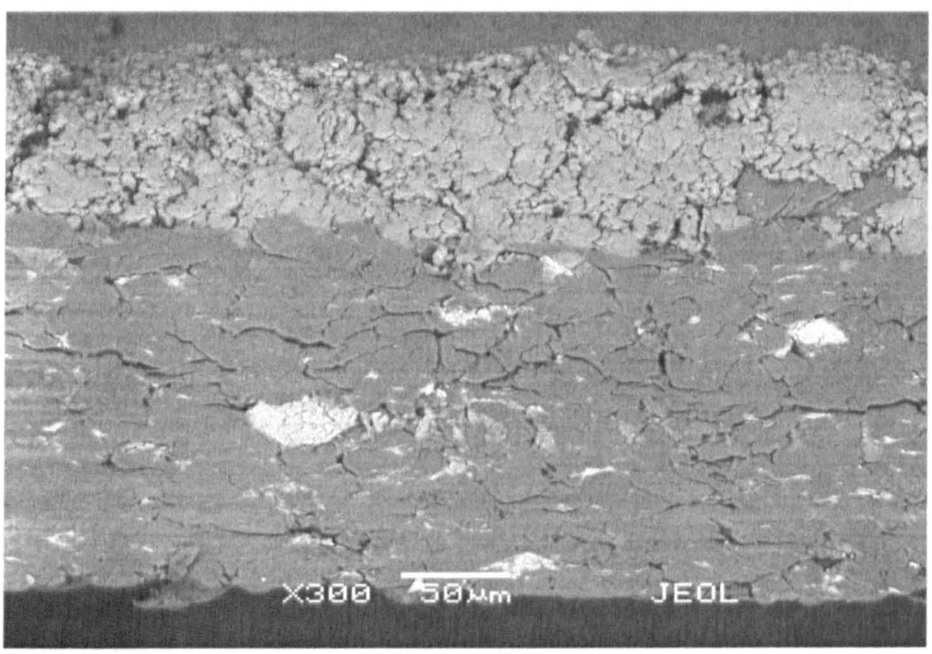

Fig. 5.60 SEM photograph of the cross-section of the Epson Presentation Matt paper (3.5) X 300.

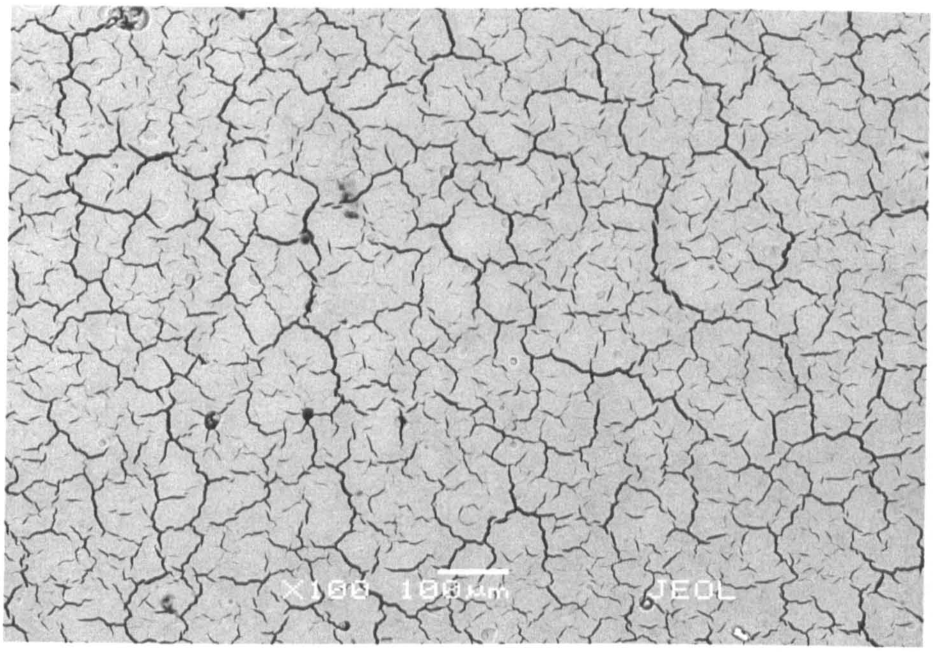

Fig. 5.61 SEM photograph of the surface of the Epson Photo Glossy paper (3.1) X 200.

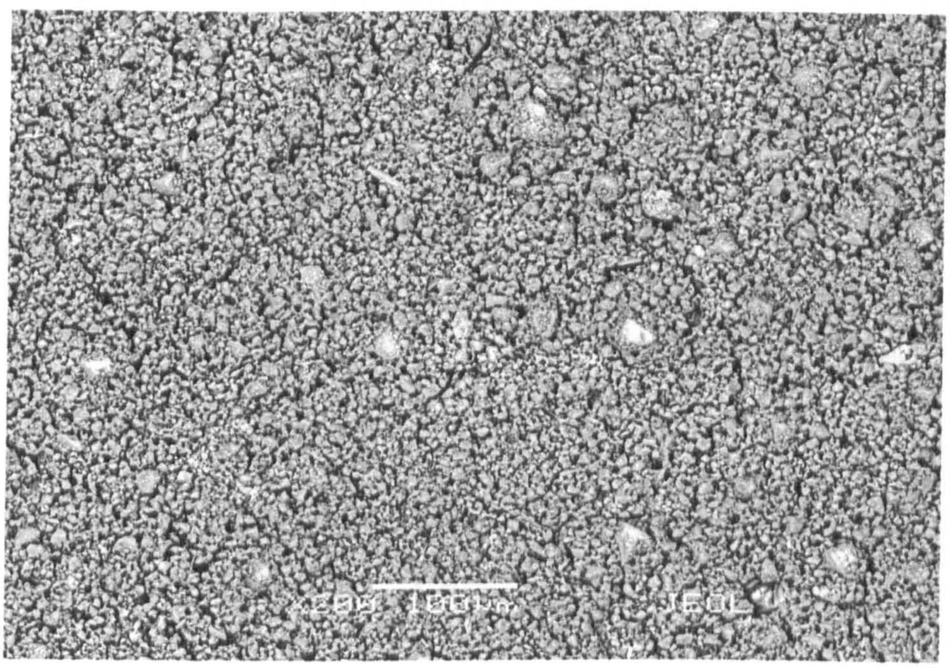

Fig. 5.62 SEM photograph of the surface of the Epson Presentation Matt paper (3.5) X 200.

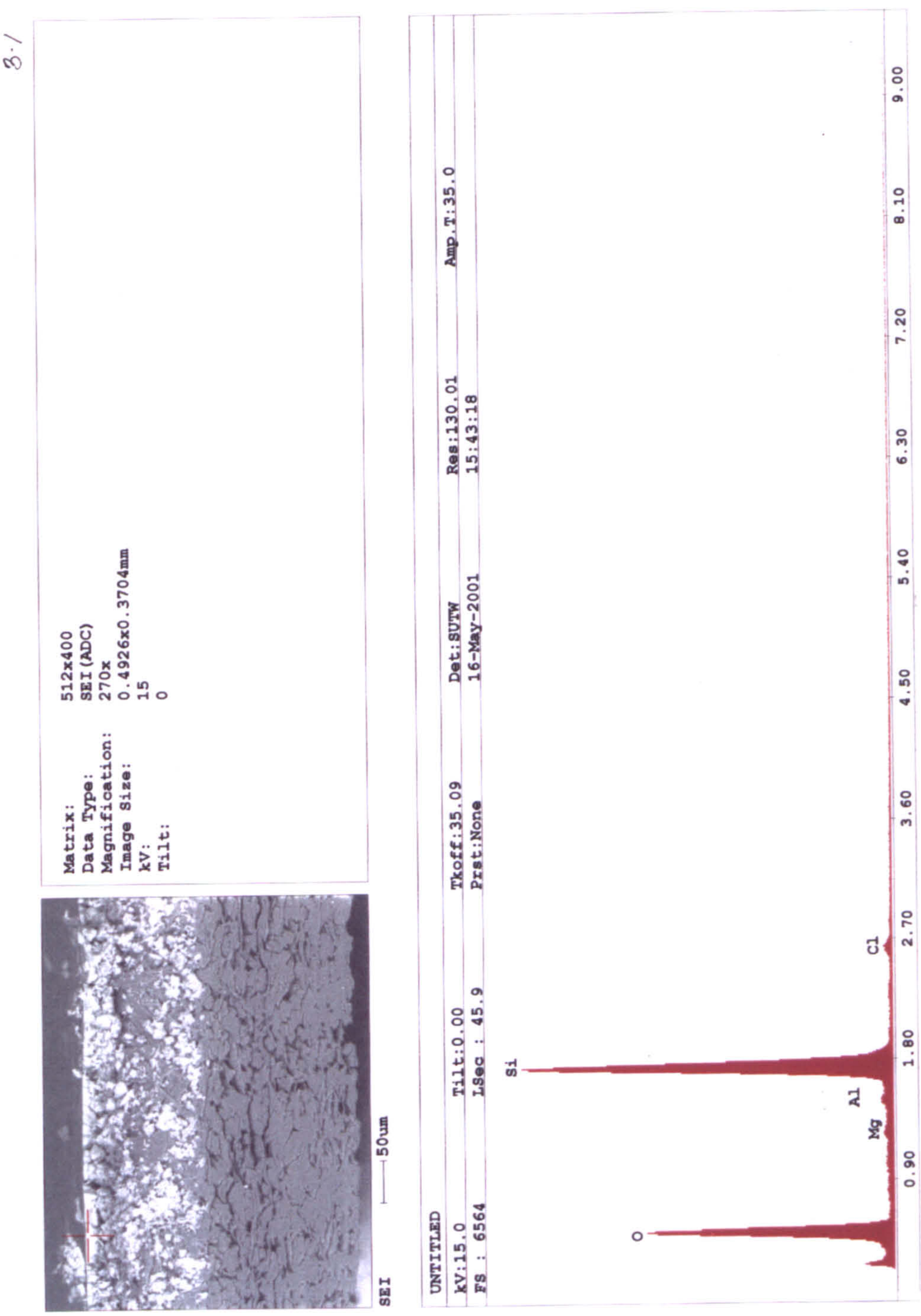

Fig. 5.63 EDS Analysis of the Epson Pro 9000 Photo Glossy paper (3.1).

3.4

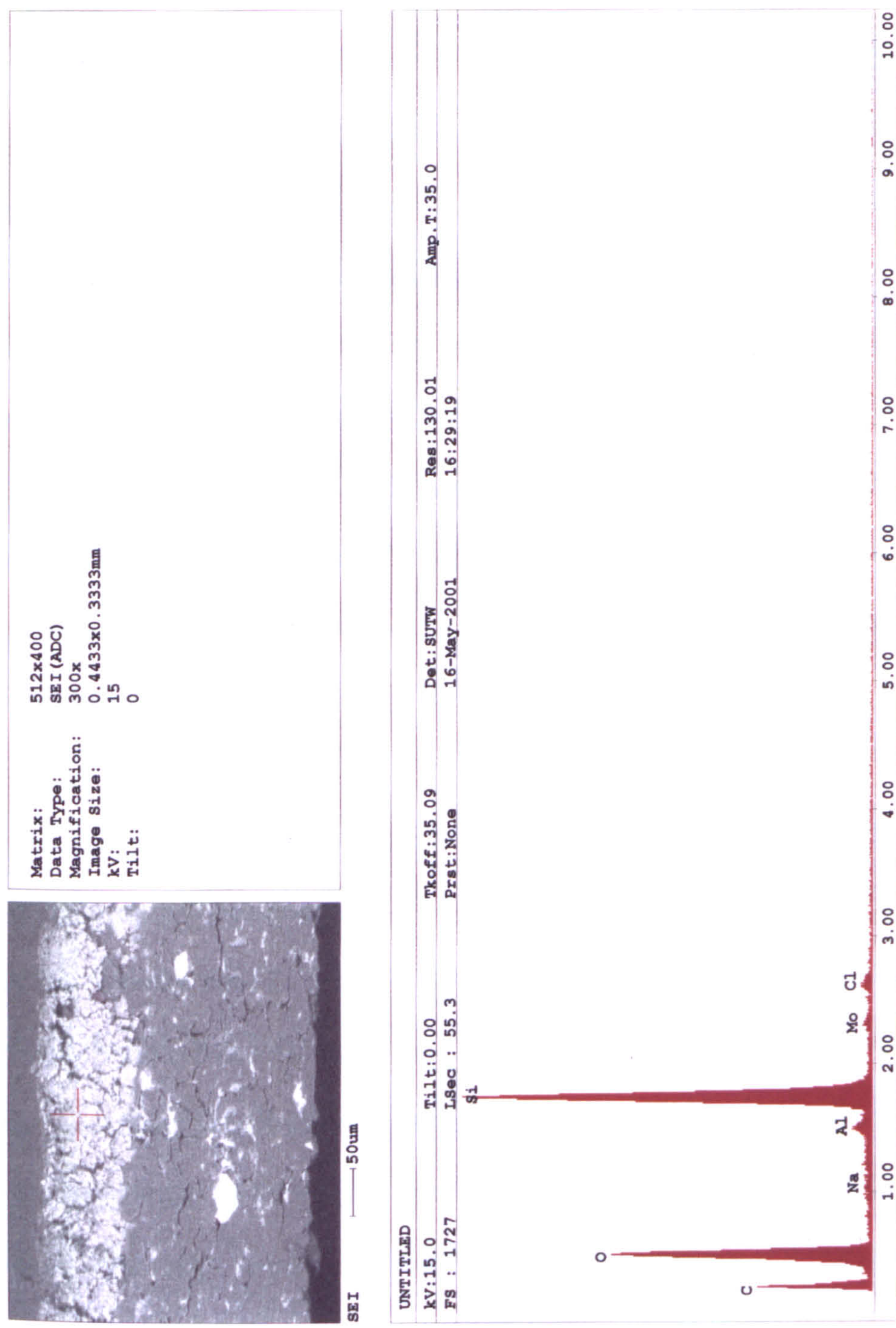

Fig. 5.64 EDS Analysis of the Epson Presentation Matt paper.

6.0 DISCUSSION OF RESULTS

6.1 PRINT QUALITY

Determination of the suitability of the printing processes used in fine art and photography reviewed in this investigation will not be discussed since this factor is at the discretion of the artists creative requirements. For each process though, there was a noticeable difference in colour, resolution, variation of grey levels, edge acuity and colour-to-colour bleed. Overall, the printer that produced the highest quality print materials was the Epson Photo Stylus 870 printer (see Appendix Q (p. Q – 541). The Iris 3047 printer was a close second in quality, but the magenta and black inks were not as vivid as the magenta and black inks from the other printed samples tested (See Appendix Q (pp. Q - 519 to Q – 521)). The Epson Pro 9000 printer was also of a very high quality but colour blend and the range of grey scales were not as good as the Iris and Photo Stylus printed samples (see Appendix Q (pp. Q – 531 to Q – 539)).

The characteristics of the Lyson samples were harder to evaluate because no print quality sample was produced (see Appendix Q (pp. Q – 523 to Q – 529)), but the black ink from the Lysonic ink set was not particularly deep in tone, and the print resolution on the coated papers was much more obvious than on the Epson or Iris prints. The Canon print samples were also difficult to assess, since, again no print quality sample was produced (see Appendix Q (pp. Q – 545 to Q – 563))., but the printing 'style' of the solid toner layer, which coats the surface of the paper rather than sinking into the substrate, rendered prints with a cruder finish than the ink jet samples. The Hewlett Packard samples were shown to have the lowest resolution of all the print samples, which greatly affected the aesthetic appearance of the print quality sample (see Appendix Q (p. Q – 543)). After reviewing the above selection of prints samples, resolution was considered the most significant factor in the grading of print quality.

6.2 ACCELERATED LIGHT TESTING

6.2.1 The effect of the substrate on the light stability of the print samples

6.2.1.1 Overview of results

The influence of the paper substrate on the light stability of the ink jet inks is evident from the results, but these findings were not as originally expected. With the Microscal, natural daylight and fluorescent light ageing tests the results showed that the Epson Pro 9000 had much better light fastness characteristics on the matched coated ink jet papers than on the traditional uncoated papers. Therefore, the general notion that the uncoated Whatman watercolour and Somerset Velvet papers would perform better than the coated papers, as previous research has shown (see 3.7.4), was not valid. Recent literature published on developments in ink jet coated paper technology (see 3.2.5) has reviewed the successful use of pH manipulation and mordants to improve the wet and light fastness of the ink jet inks once they are printed on the selected coated papers. The pH control method appears to be present for this selection of ink jet coated papers, as measurement of the pH value of these substrates by cold extraction (see 5.8.2 and table 5.22), showed that most of the ink jet coated papers were slightly acidic. The Lyson Fotonic and Lysonic ink sets, however, all showed better light fastness when printed on the traditional uncoated papers than when produced on their match coated papers.

6.2.1.2 Effect of the uncoated papers

The two uncoated papers, the Whatman watercolour and Inveresk Somerset Velvet papers, produced different light fastness results when printed with the Iris and Epson inks sets. The differences between these papers occurred under all of the light testing methods employed. The cyan and yellow inks from the Iris ink set performed better on the Whatman paper than on the Somerset paper. The magenta ink from the same ink set gave much the same results on both papers, but the light fastness of the black ink was improved slightly when printed on the Somerset paper compared to the same ink produced on the Whatman paper. In the tungsten-halogen light ageing study, all of the samples printed with the Iris ink set on the Somerset paper, exhibited slightly smaller changes in ΔE_{ab} than the same ink printed on the Whatman watercolour paper. With the Epson Pro 9000 ink set, the cyan and black inks showed slightly better light fastness when printed on the Somerset paper than on the Whatman paper; the yellow demonstrated a similar degree of fading on both papers, but the magenta ink performed significantly better on the Whatman paper than on the Somerset paper. The light fastness results of the Iris and Epson Pro 9000 ink sets were not consistent for both papers. The sample population for each of the light fast tests only included one sample of every print type, therefore, the difference observed between these two uncoated papers could be due to marginal error. The results for some of the samples printed on the two uncoated papers, however, showed a difference in colour change (ΔE_{ab}) of over 5 for the same ink. This difference is a significant value, indicating that these uncoated papers could be reacting with the inks to form images with better or worse light fastness characteristics. Further testing needs to be performed using a larger quantity of samples and greater variety of uncoated papers, to see if the above findings are consistent.

6.2.1.3 Effect of the Inveresk Somerset Velvet Enhanced (ISVE) paper

The ink jet coated ISVE paper gave the poorest and most inconsistent light fastness results overall, compared to the other paper types that were printed with the Epson Pro 9000 ink set. After exposure to the Microscal and natural daylight tests, the IVSE paper exhibited the largest ΔE_{ab} values compared to the other papers tested for all of the print samples, except for the yellow ink, which had a smaller ΔE_{ab} value on the ISVE paper than on the two uncoated papers, but a higher ΔE_{ab} value compared to the two Epson coated papers. With the samples exposed under the UV filter for 11 405 klux-hours in the fluorescent light ageing test, the black ink from the Epson Pro 9000 ink set printed on the ISVE paper faded with a ΔE_{ab} four times larger (ΔE_{ab} = 11.55) than the same ink printed on the uncoated Somerset paper (ΔE_{ab} = 2.39). However, the cyan, magenta and yellow inks from the Epson Pro 9000 ink set all showed better light fastness values on the ISVE paper than on the uncoated Somerset and Whatman papers, and the Epson coated Photo Glossy and Presentation Matt papers.

6.2.1.4 Effect of the electrophotographic papers

A difference in fading rates of the Canon print samples was observed with the Canon Ultra White paper Canon Card. The samples printed with the 1150 laser printer exhibited more rapid fading rates on the Ultra White paper (5.1) than when printed on the Card (5.2) for the cyan, magenta and yellow toners. With the samples printed with the CLBP400PS laser printer the Canon card showed a slight increase in fading of the yellow toner compared to the same toner printed on the Ultra White paper, but the other colourants exhibited much the same light fastness rates.

6.2.2 Catalytic fading of dye mixtures

Analysis of the change in ΔE_{ab} of the Microscal, tungsten-halogen and fluorescent light aged samples confirms that the phenomenon known as the 'catalytic fading of dye mixtures' (see 3.7.5) is apparent with all of the ink jet ink sets tested. The Canon electrophotographic print samples did not show any signs of catalytic fading with mixtures of the toners. Table 6.1 lists the ink jet ink sets and the combination of dyes that illustrated this phenomenon.

Table 6.1 Combinations of ink that demonstrated catalytic fading upon exposure to light

Sample No.	*Colour patches where catalytic fading of the ink mixtures has occurred*
1.1	100 % Y 50 % K – only this colour patch showed an increase in fading in the Microscal Light Fastness Tester. Overall, the catalytic effect of dye mixtures increased ΔE_{ab} by a maximum of 2 units.
1.2	100 % Y 50 % K – only this colour patch showed an increase in fading in the Microscal Light Fastness Tester. The ΔE_{ab} value was slightly greater than sample 1.1 printed on the Inveresk Somerset Velvet paper. Overall, the catalytic effect of dye mixtures increased ΔE_{ab} by a maximum of 2 units.
2.1	No catalytic fading was present in the samples tested, but combination of the cyan, magenta, and yellow inks printed with 50 % black were not light aged due to the samples not being available for testing.
2.2	100 % M 50 % K – only this colour patch showed a slightly increase in fading compared to the magenta and black ink printed separately. Overall, increase by 0.7 ΔE_{ab} units.

Table 6.1 Continued

Sample No.	*Colour patches where catalytic fading of the ink mixtures has occurred*
2.3	Sample set void, due to over heating in the Microscal Light Fastness Tester.
2.4	Red; Green; Blue; 100 % M 50 % K; 100 % Y 50 % K; 25 % and 50 % CMYK – After exposure to the Microscal Light Fastness Tester these colour patches all showed significantly larger ΔE_{ab} values than the primary inks printed on their own. The magenta and yellow inks combined with 50 % black demonstrated the largest ΔE_{ab} values which were over double the fading difference of the same inks printed singly. Overall, the catalytic effect of dye mixtures increased ΔE_{ab} by a maximum of 10 units.
3.1	Red; Green; Blue; 100 % C 50 % K; 100 % M 50 % K; 100 % Y 50 % K; 50 % CMY; 50 % CMYK – After light ageing in the Microscal Light Fastness Tester the Green, 100 % C 50 %K; 100 % Y 50 %K and 50 % CMYK colour patches all demonstrated higher ΔE_{ab} value compared to the inks printed separately (the blue ink patch was void). Due to the fading rate of the magenta ink the overall, change was increased by only 0.5 ΔE_{ab} units. In the halogen light test, all the colour patches listed except for the green showed significant larger ΔE_{ab} value than the individual inks. Overall, change was increased by only 3 ΔE_{ab} units.
3.2	100 % Y 50 % K; 50 % CMY; 50 % CMYK – In the Microscal Light Fastness Tester only these three printed patches showed a higher ΔE_{ab} value than the inks printed individually. Blue; 25 % CMY; 50 % CMY; 25 % CMYK; 50 % CMYK – these ink patches all showed a much larger fading that the individual inks printed separately after exposure to the fluorescent light ageing test (primary printing colours printed with 50 % black were not tested with fluorescent light). Overall, the catalytic effect of dye mixtures increased ΔE_{ab} of the ink set by a maximum of 5 units.

Table 6.1 Continued

Sample No.	*Colour patches where catalytic fading of the ink mixtures has occurred*
3.3	Blue; 25 % CMY; 50 % CMY; 25 % CMYK; 50 % CMYK – these ink patches all showed a much larger ΔE_{ab} value that the individual inks printed separately after exposure to the fluorescent light ageing test (primary printing colours printed with 50 % black were not tested with fluorescent light). Overall, the catalytic effect of dye mixtures increased ΔE_{ab} by a maximum of 9 units.
3.4	Blue; 25 % CMY; 50 % CMY; 25 % CMYK; 50 % CMYK – these ink patches all showed a much larger ΔE_{ab} value than the individual inks printed separately after exposure to the fluorescent light ageing test (primary printing colours printed with 50 % black were not tested with fluorescent light). Overall, the catalytic effect of dye mixtures increased ΔE_{ab} by a maximum of 8 units.
3.5	100 % M 50 % K; 100 % Y 50 % K; 50 % CMY; 25 % CMYK; 50 % CMYK – these patches have all shown an increase in fading greater than the primary ink colour printed separately, in the Microscal Light Fastness Tester. The yellow ink printed with 50 % black and the 25 % and 50 % printed concentrations of the all the primary printing colours including black demonstrated the largest ΔE_{ab} values almost double the fading difference that of the individual inks. Red: Blue; 25 % CMY; 50 % CMY; 25 % CMYK; 50 % CMYK – these ink patches all showed a much larger ΔE_{ab} value that the individual inks printed separately after exposure to the fluorescent light ageing test (primary printing colour printed with 50 % black were not tested with fluorescent light). Overall, the catalytic effect of dye mixtures increased ΔE_{ab} by a maximum of 25 units.
3.6	50 % CMYK – only this patch has demonstrated catalytic fading of the dye mixtures compared to the inks printed separately, light aged in the Microscal Light Fastness Tester. Overall, the catalytic effect of dye mixtures increased ΔE_{ab} by a maximum of 0.8 units.
4.1	Blue; 100 % Y 50 % K; – only these two ink patches showed a slightly higher ΔE_{ab} value than the individual ink printed separately, increasing by 1 ΔE_{ab} unit.

The results in table 6.1 demonstrate the importance of light testing not only the primary ink set colours but also their various combinations, as these mixtures of the inks can produce much higher fading rates than the inks alone; affecting the overall performance of the ink set. The results also show the importance of testing a wider selection of possible ink combinations than a number of previous studies have investigated (Gillet *et al.*, 2000, British Journal of Photography 2, 1999). Combinations of the cyan, magenta and yellow inks printed with 50 % of the black ink have been shown to produce some of the highest catalytic fading reactions (Iris ink set). Wilhelm Imaging Research have tested the variety of ink combinations used in this study with a larger range of different ink concentrations, and future light testing should incorporate this further selection of dye mixtures. The paper substrate has a significant role in determining the strength of this phenomenon, with the Fotonic ink set showing a higher occurrence of catalytic fading of the dye mixtures on the uncoated Whatman paper than on the Lyson Rough Fine Art coated paper. The Epson Pro 9000 ink set had the opposite relationship, where catalytic fading of the dye mixtures occurred more on the coated papers and with a larger ΔE_{ab} value than on the uncoated papers.

Only the various different ink combinations printed with the Epson Pro 9000 ink set were tested with different light sources. The results showed that the Microscal, halogen and fluorescent light tests did not produce the same results. The differences occurred on the red, green, blue, and the primary printing ink colours printed with 50 % black. However, the patches composed of combinations of the primary colours printed with and without black, all showed a similar contrast under the different light sources. This result suggests that the difference in fading with the various light sources could be due to the spectral distribution of the lamps and the spectral absorption characteristic on the different ink patches.

The catalytic fading of the Epson ink patches compared to the individually printed cyan, magenta, yellow and black colours, may also not be a true representation of the extent of the accelerated fading. This is because, under microscopic examination, the primary ink patches can be seen to be composed of all the ink colours and not just the particular primary ink colours.

The fading rates of the patches containing combinations of the Canon toner, did not exhibit the catalytic phenomenon for any of the samples tested. The occurrence is documented to occur with dyes, and toners are generally formed from pigments, therefore, this phenomenon may not occur with electrophotographic printed materials.

The Microscal Light Fastness Tester produce uneven illuminance levels around its perimeter (see 5.2.1 and 5.2.2). Therefore, the comparison of ΔE_{ab} results calculated from the tests could be inaccurate. The results of the samples that showed slight catalytic fading of the dye mixtures could react differently under a light source that radiates light more evenly.

6.2.3 Effect of ink concentration on the rate of fading

The effect of ink concentration on the light fastness of the different ink sets tested was found to be inconsistent with the previously published findings by Allred *et al.* (1994), which investigated the light ageing of contone Iris print samples (see

3.7.6). The ink regions that showed the largest change under the light ageing tests were at print concentrations of either 75 % or 50 % for most of the inks tested including the Iris print samples. Only the black ink from the Lysonic ink set printed on Whatman paper (2.3), the yellow ink from the Epson Pro 9000 ink set printed on the Whatman paper (3.4), and the black toner from the Canon CLC 900 printer (5.3) followed the fading pattern of the previous research. These inks/toners showed a greater degree of fading at the lower ink concentration of 25 % (this occurred at 20 % in the research by Allred *et al.* (1994)), and the fading rate of the other ink/toner patches fell as the ink concentration increased.

For some of the inks, the largest fading change occurred on the 100 % ink printed patch, which conflicts with the conclusions published by Allred *et al.* (1994). The authors of the previous research concluded that internal reflectance of light within the paper substrate, which was increased where ink jet dots were discretely printed, was responsible for the accelerated fading rates of the Iris ink jet samples tested at low print concentrations. In this present study, ten different inks and one toner showed the greatest fading rates at the highest print concentration of 100 % ink. All of these colourants showed different light fastness ratings and different fading characteristics on the various papers tested. Table 6.2 lists the inks/toners that demonstrated the greatest degree of fading on the 100 % printed ink patch. The light sensitivity rating of the ink/toner is given using a subjective scale which compares the overall ΔE_{ab} value of the particular ink/toner with the other three inks from the ink set (1 for most sensitive ink/toner to 4 for the least sensitive ink/toner).

Table 6.2 List of print samples that exhibited the most rapid fading rates printed at 100 % ink/toner concentration compared to the same ink/toner printed at lower print concentrations. The light sensitivity of the particular ink/toner has been given a subjective rating by comparing the ΔE_{ab} value of the ink/toner patch to the ΔE_{ab} values of the other primary printing inks/toners from the same ink set, to examine any trends (1 for most sensitive ink/toner to 4 for the least sensitive ink/toner).

Sample No.	*Ink (100 % concentration)*	*Paper*	*Sensitivity Rating (1-4)*
3.1	Epson Pro 9000 Magenta	Epson Photo Glossy	1
3.1	Epson Pro 9000 Yellow	Epson Photo Glossy	4
3.2	Epson Pro 9000 Yellow	ISVE	4
3.3	Epson Pro 9000 Cyan	Inveresk Somerset	3
3.4	Epson Pro 9000 Cyan	Whatman	3
3.5	Epson Pro 9000 Cyan	Epson Presentation Matt	4
3.6	Epson Photo Stylus 870 Cyan	Epson Photo Glossy	2
3.6	Epson Photo Stylus 870 Magenta	Epson Photo Glossy	3
4.1	Hewlett Packard 3500 DesignJet Cyan	Hewlett Packard Heavy Coated Matt	2
4.1	Hewlett Packard 3500 DesignJet Magenta	Hewlett Packard Heavy Coated Matt	1
5.1	Canon 1150 Colour Laser Yellow	Canon Ultra White	1

The results listed in table 6.2 shows that there is no particular relationship between ink density and fading rate, taking into consideration the paper type, print resolution, light source, and sensitivity of the ink to light. Therefore, no conclusions have been drawn from this outcome. For a fuller understanding of the fading process of these samples, further light testing of the samples using a wider range of print densities (at 10 % ink concentration steps) and ink at different dilutions is suggested.

Many of the inks exhibited a higher fading rate at print concentrations of 75 % and/or 50 %. This result could be due to the combination of internal reflectance within the paper substrate on unprinted areas and the level of ink concentration available for fading. Visual examination of the samples that were light aged in the Microscal Light Fastness Tester often showed that for the patches that faded more rapidly at print concentrations of 75 % or 50 %, some colour was still left on exposed area. The patches containing the same ink printed at 50 % and/or 25 % ink concentrations had little or no colour left. Further light testing using a wider range of ink concentrations and ink dilutions at a lower illumination level so that the fading rate of the ink patches can be plotted needs to be tested, to obtain a better understanding of the effect of print concentration with light fading.

The different print concentrations of Epson Pro 9000 ink set samples were exposed to wavelengths of 400 nm and above (no UV radiation) with the fluorescent and tungsten-halogen light tests, and to wavelengths of 310 nm and above (containing near UV radiation) with the Microscal light tests. Very little difference was observed with the fading rates of the different ink concentrations between these three exposures indicating that the spectral distribution and irradiance of the light source is not of significant importance for determining the degree of difference in fading of the four different print concentrations tested. It is considered that future investigations into the effect of print concentration should still incorporate a range of light sources, as particular ink sets could produce different results.

6.2.4 Photochromism

6.2.4.1 Background

Photochromism is the term given to a phenomenon that occurs in some dyes that change colour reversibly upon exposure to light. The occurrence of this phenomenon is normally considered a defect in textile dyes (Gordon and Gregory, 1987), but the dyes are sometimes used to produce novelty toys and clothing. Photochromism is recognized to occur in the azobenzene dyes caused by the *transcis* isomerism about the azo linkage (N=N). The process can be summarised by the following:

$$\textit{trans} \underset{h\nu \text{ or heat}}{\overset{h\nu}{\rightleftharpoons}} \textit{cis}$$

As discussed in 3.2.3.5, colourants used for ink jet inks are commonly azo dyes. Photochromism is known to occur with some azo dyes[1] and displays itself as a *bathochromic shift* (the colour darkens on exposure to light). The *cis*- and *trans*-azobenzene structures have three accessible excited states, corresponding to three absorption bands in the visible and near UV spectrum. The lowest transition occurs at approximately 440 nm and 430 nm in *trans*- and *cis*-azobenzene, respectively (Griffiths, 1972). Since the *cis*-isomers absorb at shorter wavelengths than the *trans*-isomers, the shade change on exposure to light can be quite pronounced. The rate of the *trans-cis* reaction is temperature dependent, and the proportion of the *trans*-isomer increases at lower temperatures, whereas the reverse *cis-trans* process is generally temperature independent (Griffiths, 1972). The rate of the photochromic reaction is recognised to accelerate with acid catalysts, and is sensitive to different solvents (Ross and Blanc, 1971). The ink jet coated papers are often made to be slightly acidic to quicken the drying process and improve the wet fastness of the ink (see 3.2.5). Some of the ink jet papers tested in this study were found to have a pH of between 5.2 and 6.4 (see 5.8.2). Most of the photochromatic reactions occurred on these acidic ink jet coated papers, except for the cyan ink from the Lyson Fotonic and Lysonic ink sets, which showed photochromatic reactions when printed on Whatman watercolour paper and not when on the matched Lyson Fine art papers. After thermal ageing, the pH value of the Whatman watercolour paper was found to significantly change from a pH average of 8.3 to a pH average of 6.2, but the pH values of the Lyson Soft Fine Art and Rough Fine Art papers were found to stay relatively neutral (7.3 and 7.1 respectively after thermal ageing). However, this relationship of acidity and the occurrence of photochromism did not manifest itself with the cyan and yellow inks from Epson Pro 9000 ink set printed on Epson Presentation Matt paper, which has a pH value of 7.8, and falling to 7.4 after thermal ageing.

On polymeric substrates, particularly where the dye is molecularly dispersed within the polymer, the lifetime of the *cis*-isomer can be greatly increased. Photochromism is also inhibited by strong hydrogen bonding of the dye to the substrate, and thus it is more noticeable on the newer synthetic fibres, which are generally without sites for hydrogen bonding (Griffiths, 1973). This mechanism would appear to apply to the results collected in this study, where more pronounced photochromatic reactions occurred on the ink jet coated papers. These papers are designed to restrict the ink droplets from blending with each other and the paper substrate underneath, and maintain all the ink near the surface of the paper. The uncoated papers allow for the ink to penetrate the fibres and for hydrogen bonding to occur between the inks and paper.

6.2.4.2 The occurrence of photochromism in this investigation

Irregular fading rates were recorded on a selection of samples exposed to natural daylight, tungsten halogen and fluorescent light fastness tests. Further light testing was performed using the method published by the British Standards Institute for the identification of photochromism (BS 1006 B05, 1990), and the phenomenon was found to occur on some of these samples (see 5.6).

The test for photochromism performed in this study only investigated the change in colour of the samples after they were removed from exposure to light (the reverse *cis-trans* reaction) over a period of 24 hours, as suggested by the published test. Further analysis of the results for the samples identified to be photochromatic (see 5.6), showed that the rate of the *cis-trans* reactions for two of the samples seemed to obey an exponential relationship (see fig. 5.45 and 5.46). However, the *cis-trans* reactions of the other samples tested did not show this relationship (see Appendix M (pp. M – 489 to M - 490). Further testing, taking more frequent colour measurements, is required to establish if the photochromatic reactions follow an exponential relationship.

Irregular fading rates of the cyan and yellow inks from the Epson Pro 9000 ink set, printed on Epson Photo Glossy paper (3.1), was evident on exposure to the Halogen light fading test (1,000 lux (+/- 100 lux) with UV radiation filtered out). Although this level of illumination does not exist within a museum or gallery environment, the level can be present in office and public buildings (Wilhelm *et al.* 1994). Further testing would need to be conducted to investigate whether the irregular fading rates occurs at lower illuminance levels of 50 lux to 200 lux.

The colour measurement results from the samples exposed to the Microscal Light Fastness Tester failed to demonstrate irregular fading rates on any of the samples tested. This could be due to the light source emitting a high irradiance of light and therefore, measurements were not frequent enough to record an irregular fading rate, or that the irradiance of light and the heat transmitted by the source affected the rate of fading, suppressing some of the reactions (see 3.5.2, Reciprocity failure).

6.2.5 The effect of the physical state of the dye on the fading rate

The disintegration of the dye particles in the ink could be another contributing factor to the erratic fading curves. The aggregation or physical state of the dye in a polymer substrate is an important parameter in controlling photo-fading (Giles *et al.*, 1980, Allen, 1991). The rate of fading of dyes can be divided into following five different types (see fig. 6.1).

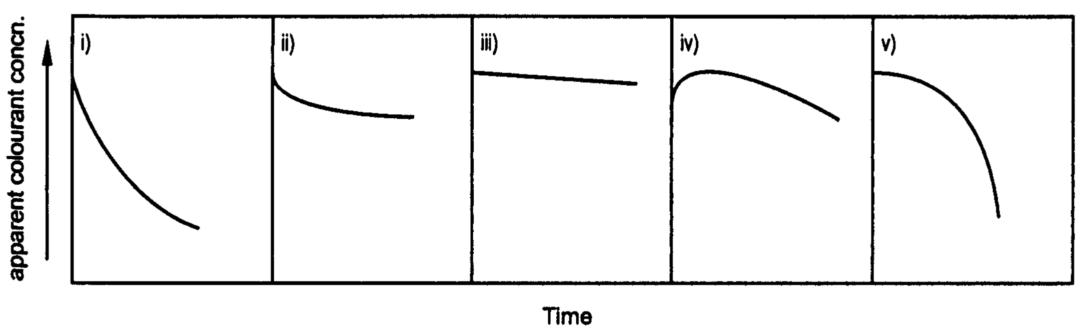

Fig. 6.1 Diagram of typical fading rate curves of colourants in polymers.

i) First- or second-order fading. Dye probably in molecular dispersion, or very small aggregates.
ii) Initially as i), followed by a slow fading at constant rate (zero order).
iii) Entirely constant fading rate.
iv) Negative initial fading, caused by disintegration of colourant particles in heat of illumination.
v) Fading which accelerates with time. Caused by continual break down of colourant particles.

Curve iv) shows a negative fading rate, attributed to the disintegration of the dye particles caused by heating during illumination. This phenomenon occurs quite often with fast dyes (Giles *et al.*, 1980, Allen, 1991). The apparent increase in colour intensity in curve 'iv' is attributed to the breakdown of particles occurring more rapidly than the fading reactions. On exposure to light, the dye aggregates breakdown into smaller particles causing the intensity or saturation of the dye to increase, leading to a negative fading curve. The dye particles then undergo photochemical reactions, which cause the dye to fade, producing a positive fading curve. The particles can then undergo further disintegration and the process is repeated until the all the particles have been broken down. This type of fading rate can produce erratic fading curves similar to the results found in this investigation (Allen, 1991).

Only some of the samples that produced irregular fading rates were shown to be photochromatic (see 5.6). Therefore, the breakdown of dye particles could be contributing to the erratic fading behaviour of the other printed samples. Most of the irregular fading rates measured in this investigation were found to occur on the samples printed on the coated ink jet papers instead of the uncoated Whatman and Somerset Velvet papers, when exposed to the full visible spectrum (except for the Epson Pro 9000 yellow ink printed on Whatman paper). The formulation of the coatings for ink jet papers often encourages the dye molecules to form aggregates once printed on the paper, to increase the light fastness of the colourant (see 3.2.5). Therefore, it is possible to consider that the dyes from the inks tested in this study have formed aggregates in the paper coatings, and that these aggregates are breaking down on exposure to light.

6.2.6 Analysing the effect of the UV filter

Analysis of the data collected from the natural daylight ageing tests show that using an UV filter makes a marked difference in reducing the fading rate of all the samples tested. This result corresponds to the findings of previous research. In particular, the Epson 3.6 sample exposed under the UV filter showed hardly any visible signs of fading (yellow had faded very slightly) after the test compared to the control. On the uncovered 3.6 sample, the cyan and magenta ink had under gone noticeable fading, which could possibly be due to the presence of pollutants in the testing environment[2] as well as light damage (see 3.7.3).

The inks that demonstrated high light sensitivity (ΔE_{ab} of 10 and above after 50 million lux hours) still exhibited large ΔE_{ab} values but to a lesser degree than the uncovered samples (an average ΔE_{ab} of 5 and above). The yellow ink from the Epson Pro 9000 printed on Inveresk Somerset Velvet Enhanced paper (3.2) was the only ink to show a dramatic improvement in light fastness with the application of the UV filter, improving from a ΔE_{ab} of 12.71 for the uncovered sample to a ΔE_{ab} of 0.52 for the UV filter protected sample.

Table 6.3 Average percentage of improvement in light fastness for the CMYK print samples exposed to natural daylight under UV filters.

Printing Manufacturer	*Sample No.*	*Average Percentage of Improvement in Light fastness using the UV Filter*
Iris	1.1	42
	1.2	53
Lyson	2.1	75
	2.2	59
	2.3	61
	2.4	57
Epson Pro 9000	3.1	48
	3.2	51
	3.3	35
Epson Photo Stylus	3.6	67
Hewlett Packard	4.1	65
Canon	5.1	43
	5.2	38
	5.3	35
	5.4	23
	5.5	37
	Average Percentage	**46**

Overall, the UV filter led to a 46 % improvement in light fastness of the samples tested (see table 6.3). This value compares with the findings published by Padfield (1966) on the benefits of using UV filters, who found that "*on average the UV absorber gave about 40% improvement in light-fastness*"[3].

6.2.7 Assessment of the fluorescent light ageing test and the effect of the dichroic colour filters

The largest ΔE_{ab} values were observed with the samples exposed to the full spectrum of fluorescent light under the UV filters. The samples exposed to limited regions of the spectrum under the dichroic filters faded more slowly. This is to be expected because the filters allowed less light to be transmitted overall. The majority of the results for the samples exposed under the dichroic filters showed irregular fading rates. This unexpected irregularity was smaller than the variations found with the inks established to be photochromatic (see 5.6), but applied to many of the patches that contained combinations of the inks found to be photochromatic. Generally, the irregular fading rates occurred with the samples exposed to the violet and blue dichroic filters, which transmitted a large percentage of the shorter visible wavelengths (400 nm – 500 nm). The irregular fading rates did not tend to occur with the same samples exposed to the filters that transmitted smaller quantities of the shorter wavelengths or the mid to long wavelengths only (the green, yellow and orange dichroic filters) (see table 6.4 for wavelength bands transmitted by the filters and fig 4.1). However, the black patch on samples 3.3 and 3.4 and the magenta patch on sample 3.5 (see fig. 6.5 and Appendix J for graphs (pp. J – 417, J - 425), showed erratic fading rates under all the dichroic filters used, and in previous tests, these ink patches exhibited no photochromatic reactions.

Overall, the results compare with previous published findings (Saunders *et al.*, 1994, Kenjo, 1986, McLaren, 1956) in that the degree of damage decreases as the length of the wavelength increases. This effect is enhanced by the fact that the violet and blue filters transmit the least amount of irradiance (see table 6.4) compared to the other filters used for the duration of the test. For most of the ink patches, the violet and blue filters produced the greatest fading rates. Selective regions of the entire visible spectrum were not assessed in this study due to limited space in the fluorescent light fast tester and the variety of inks and papers required for assessment. Instead, all the samples tested were exposed to the more damaging wavelengths of violet, blue and green wavebands. The CMYK patches, produced at 100 % ink concentrations for the Epson 3.2, 3.3, 3.4, 3.5 sample sets, were also exposed to the yellow and orange dichroic filters. Although the full visible spectrum was not assessed, the main objective of the test was to investigate the damage caused by the violet to green wavelengths of light, which are emitted strongly by fluorescent light sources.

Table 6.4 Amount of light transmitted by dichroic filters compared to the UV filter. All UV radiation was filtered out before passing through the dichroic filters (also see 4.3.3 and fig. 4.1).

Filter Type	*Wavelengths Transmitted (nm)*	*Total Exposure, H of Light Transmitted by Dichroic Filters (Whm^{-2})*	*Percentage Difference of light transmitted by Dichroic Filters Compared to the UV Filter*
U.V	400 - 700	518 977	-
Violet	400 – 455	75 884	Transmitted approximately 85 % less light.
Blue	400 – 500	92 430	Transmitted approximately 82 % times less light.
Green	400 – 570	112 117	Transmitted approximately 78 % times less light.
Yellow	400 – 410; 485 – 700	228 248	Transmitted approximately 56 % times less light
Orange	535 – 700	143 181	Transmitted approximately 72 % times less light.

Large irregularities in the fading rates, similar to the irregular fading rates of the samples that were shown to be photochromatic in previous light tests (see 5.6), were produced with the cyan and yellow inks from the Epson Pro 9000 and Iris ink sets on nearly all of the different papers exposed under the dichroic filters. In previous tests, irregular fading rates were only observed with the cyan and yellow inks from the Epson Pro 9000 ink set printed on the coated Epson Photo Glossy and Presentation Matt papers, and with the yellow ink printed on the two uncoated papers. Under the dichroic filters, uneven fading rates appear to have developed in the cyan and yellow patches from the Epson Pro 9000 and Iris ink sets on nearly every paper investigated (see fig. 6.2 and Appendix J (pp. J – 406, J – 412, J – 416 to J - 417, J - 421 , J - 426)). The erratic fading rates have also occurred on some of the ink patches that are composed of the cyan and/or yellow inks: the red and green patches from the 3.3, 3.4 and 3.5 sample sets; the blue patch on sample set 3.2; all of the composite grey scale ink patches from the 3.5 sample set (see fig. 6.3 and Appendix J (pp. J – 418 to J - 428)). A possible reason for these results could be the restricted range of wavelengths transmitted by the filters. These wavelengths could be activating a *trans-cis* photochromatic reaction that would otherwise be dominated by the longer wavelengths of the full visible spectrum. As discussed in 6.2.4, the lowest-energy transitions in the *trans-* photochromatic reaction of the azobenzene molecule occur at approximately 440 nm, and the reverse *cis-* reaction is activated by approximately 430 nm (Griffiths, 1972). Both these wavelengths are transmitted by the violet and blue dichroic filters, but the complex structures of the inks may have caused a shift in the wavelength absorption regions.

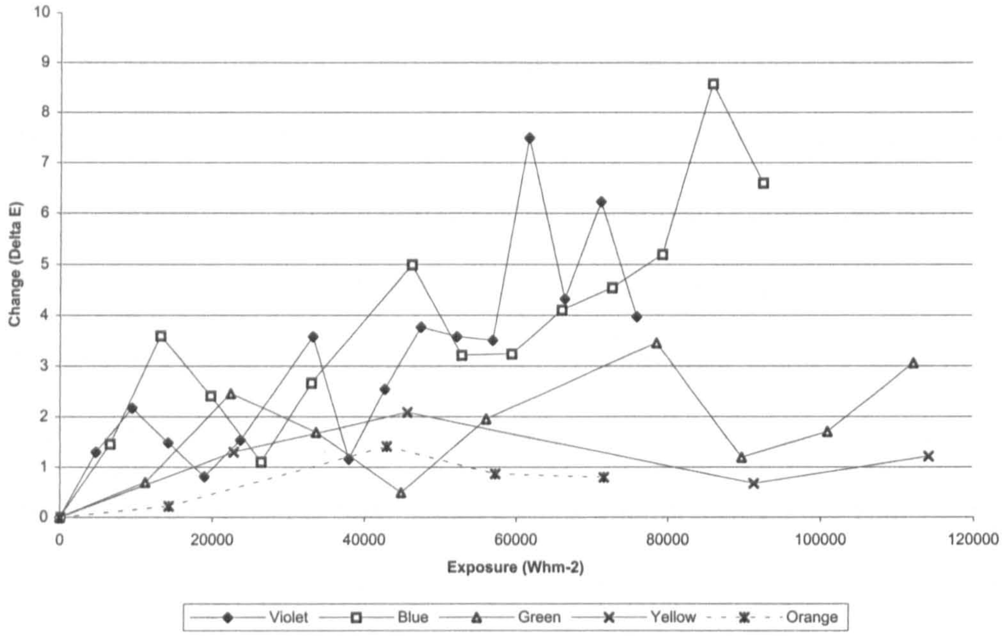

Fig. 6.2 Plot showing the change in ΔE_{ab} against exposure of the yellow ink patch from Epson Pro 9000 ink set printed on Whatman watercolour paper (3.4) after exposure to the fluorescent light fastness tester with the full range of dichroic filters employed.

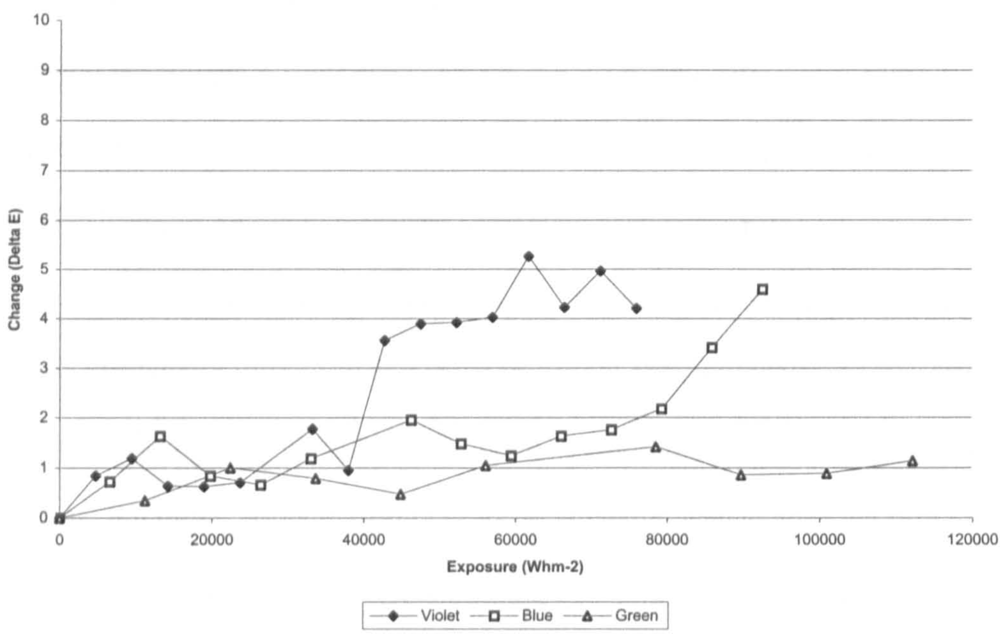

Fig. 6.3 Plot showing the change in ΔE_{ab} against exposure of the green ink patch from Epson Pro 9000 ink set printed on Whatman watercolour paper (3.4) after exposure to the fluorescent light fastness tester with the violet, blue and green dichroic filters.

Irregular fading rates were also observed with the four grey scales composed from the CMYK inks from the 3.5 Epson sample set, and the blue printed patch composed from the cyan and magenta inks from the 3.2 Epson sample set, when exposed under the violet, blue and green dichroic filters (see fig. 6.4 and Appendix J (pp. J – 413 to J - 429) for graphs). The irregular fading rates of these patches can be attributed to the fact that each patch contained either the yellow and/or the cyan ink(s) that were shown to be photochromatic in previous tests (see 5.6). The erratic fading rates, however, were not consistent for all of the patches that were composed with the photochromatic inks, therefore the particular ink and paper combination must be contributing to these reactions.

Slight erratic fading rates were also observed after exposure to the violet and blue dichroic filters, with the magenta ink from the Epson Pro 9000 samples printed on the Epson Presentation Matt (3.5) paper, and the black ink printed on the uncoated Somerset Velvet (3.3) and Whatman (3.4) papers (see fig. 6.5 and Appendix J (pp. J – 417, J - 425)). The magenta ink from the Iris 1.1 and 1.2 sample sets showed irregular fading rates as well, exhibiting curves with large fluctuations on exposure to the violet, blue and green dichroic filters (see fig 6.6 and fig. 5.28). These large fluctuations were not observed with the previous light investigations using the full visible spectrum. The considerable irregularity of the fading curves of the Iris magenta ink could indicate the presence of photochromatic reactions not previously detected with the other light ageing methods. Examination of the fading rate of the magenta ink sample exposed to the fluorescent light under the UV filter (see fig. 6.7) shows that the ink has an initial rapid fading rate which then decreases slightly after 195 klux hours. This reaction could also be attributed to the disintegration of the dye particles, but this process is known to be activated by heat from illumination and the large irregular fading rates were not observed in previous light tests where heating of the samples occurred. The slight variable fading rate of the Epson magenta and black ink patches could also be due to photochromism or standard error of the colour measurements, because only one patch was tested for each sample type.

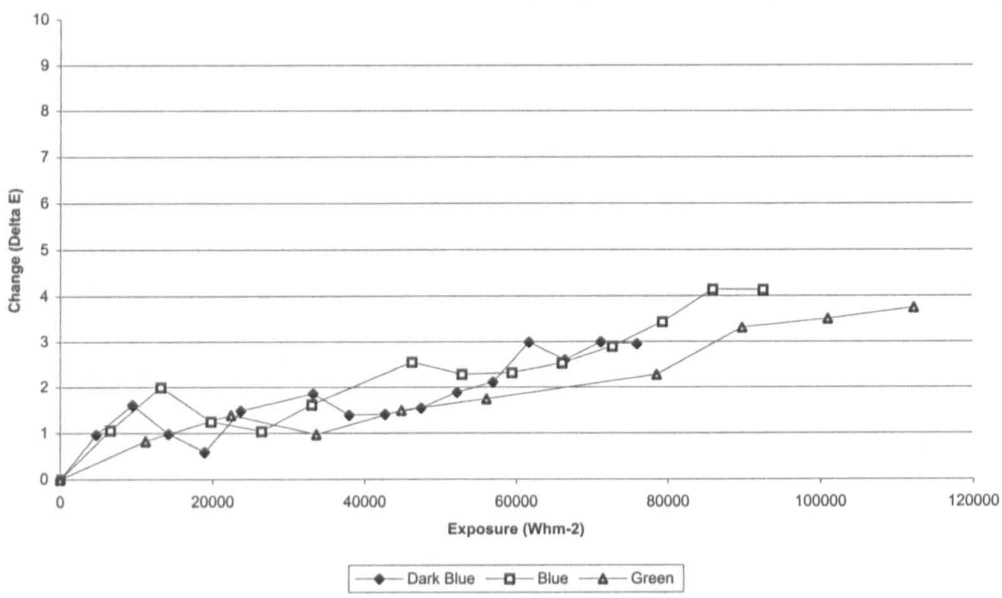

Fig 6.4 Plot showing the change in ΔE_{ab} against exposure of the 50 % CMYK ink patch from Epson Pro 9000 ink set printed on Epson Presentation Matt paper (3.5) after exposure to the fluorescent light fastness tester with the violet, blue and green dichroic filters.

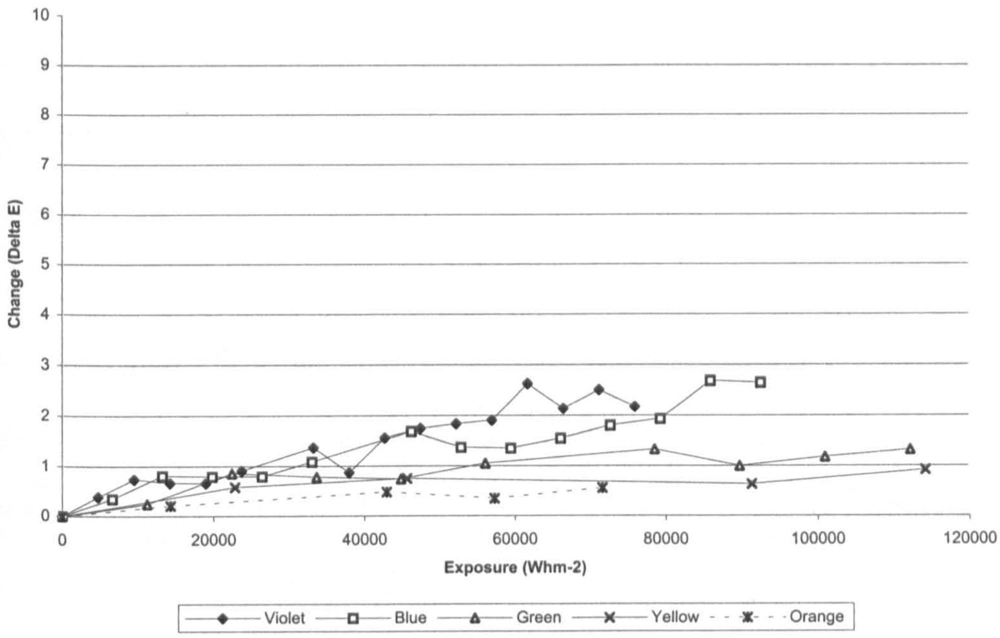

Fig 6.5 Plot showing the change in ΔE_{ab} against exposure of the black ink patch from Epson Pro 9000 ink set printed on Whatman watercolour paper (3.4) after exposure to the fluorescent light fastness tester with the full range of dichroic filters employed.

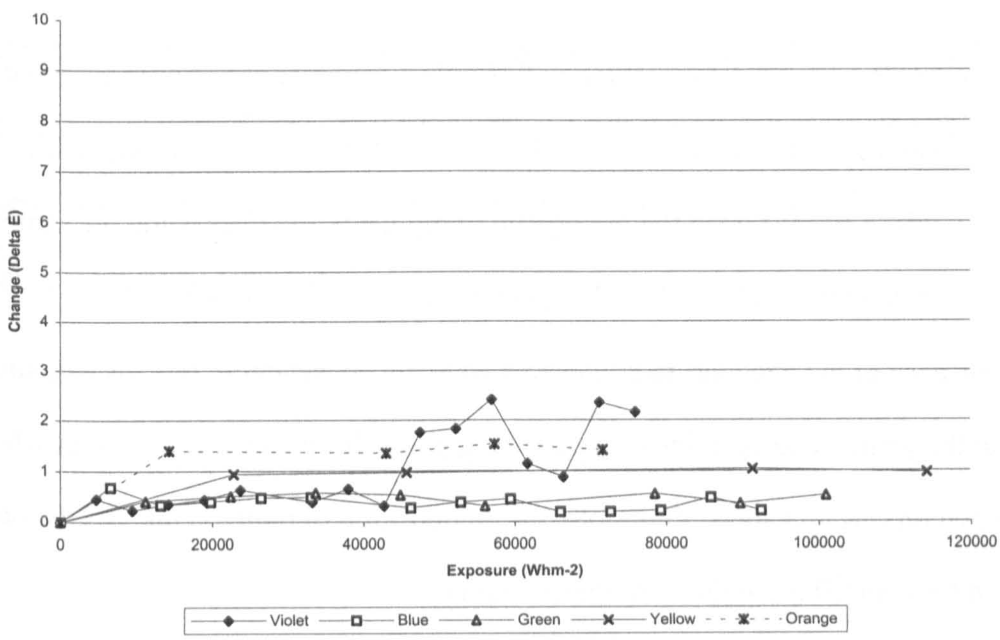

Fig 6.6 Plot showing the change in ΔE_{ab} against exposure of the magenta ink patch from Iris ink set printed on Somerset Velvet paper (1.1) after exposure to the fluorescent light fastness tester with the full range of dichroic filters employed.

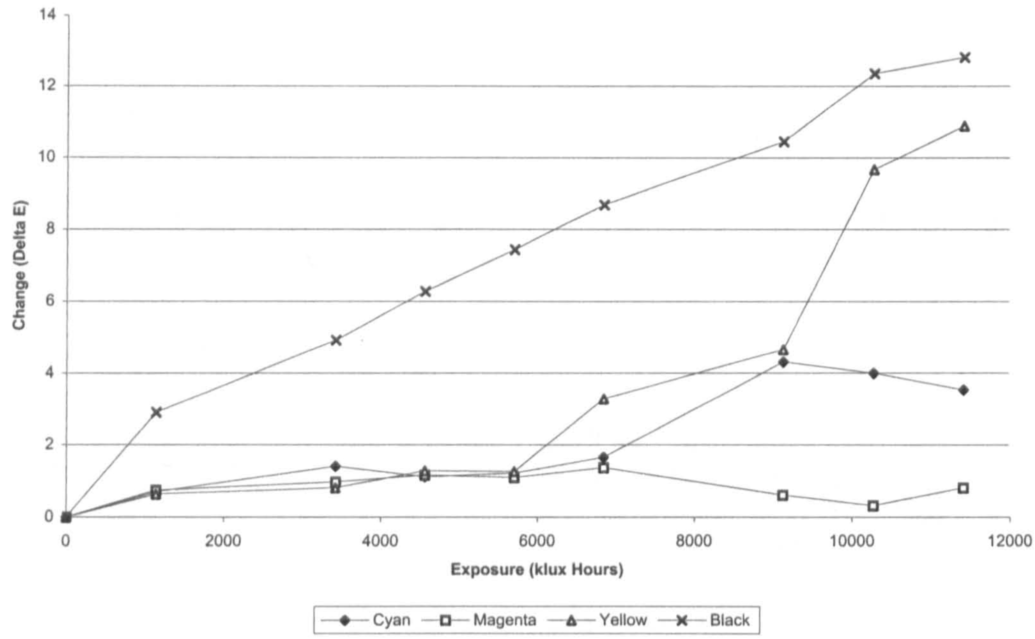

Fig 6.7 Plot showing the change in ΔE_{ab} against exposure of the CMYK inks from the Iris ink set printed on Somerset Velvet paper (1.1) exposed to the fluorescent light fastness tester with an UV filter only. The magenta ink patch does not show the same erratic fading pattern of the same ink patch exposed to the same light source with the dichroic filters (see fig. 6.6).

The variable fading rates measured in this investigation have not been reported in previously published literature (Saunders *et al.*, 1994, Kenjo, 1986, McLaren, 1956), which have studied the fading rate of pigments and dyes using the same light testing method of dividing the spectrum into separate regions. The occurrence of the irregular fading curves were not consistent in this investigation, with the yellow and cyan inks only showing photochromatic type reactions when printed on certain papers. Therefore, the composition of both the ink and the paper must be a contributing factor to these findings.

The irregular fading rates of the samples made it difficult to assess the effect of the different dichroic filters. In similar work published by Saunders *et al.* (1994) on the light fastness of artists' pigments, the relationship between the wavelength of irradiation and damage, the function D(λ), was calculated by interpolation of the plotted results. The same method was considered for this study but the strong variations in the fading rates for many of the graphs meant that the process was inappropriate. Instead, the overall fading trend produced by each filter was assessed.

The results for the all of the CMYK inks tested show that each of the spectral regions investigated contributes to the total fading of the ink patches if the wavelengths are absorbed by the colourant. Even the longer yellow and orange wavelength regions are photochemically active, which agrees with the findings of McLaren, 1956, Saunders *et al.*, 1994, and Wilhelm *et al.*, 1994[4]. Examination of the spectral reflectance curves of the cyan and blue printed patches show that a large majority of the wavelengths in the violet and blue regions of the spectrum are being reflected by these colourants (see fig.6.8 and Appendix L (pp. L – 461 to L - 484)), but all of these patches still exhibited fading on exposure to the dichroic filters transmitting violet and blue light. This result shows, therefore, that even when absorbed in minimal quantities, the shorter wavelengths are still contributing to the fading reactions.

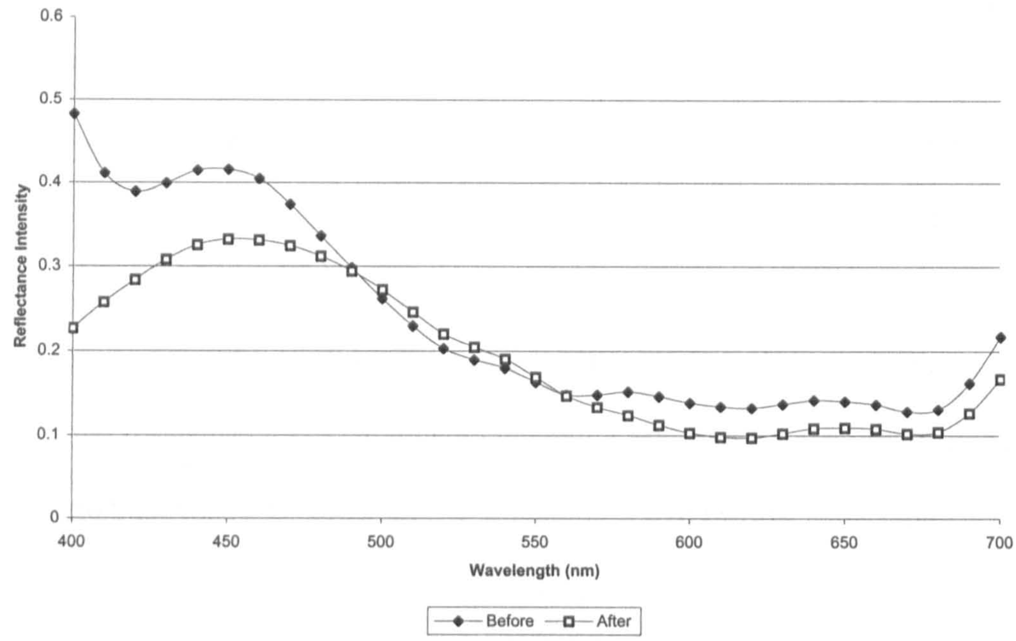

Fig 6.8 Spectral reflectance curve for the blue printed patch from the Epson Pro 9000 ink set printed on Whatman paper (3.4) after exposure to the fluorescent light fastness tester with the UV filter.

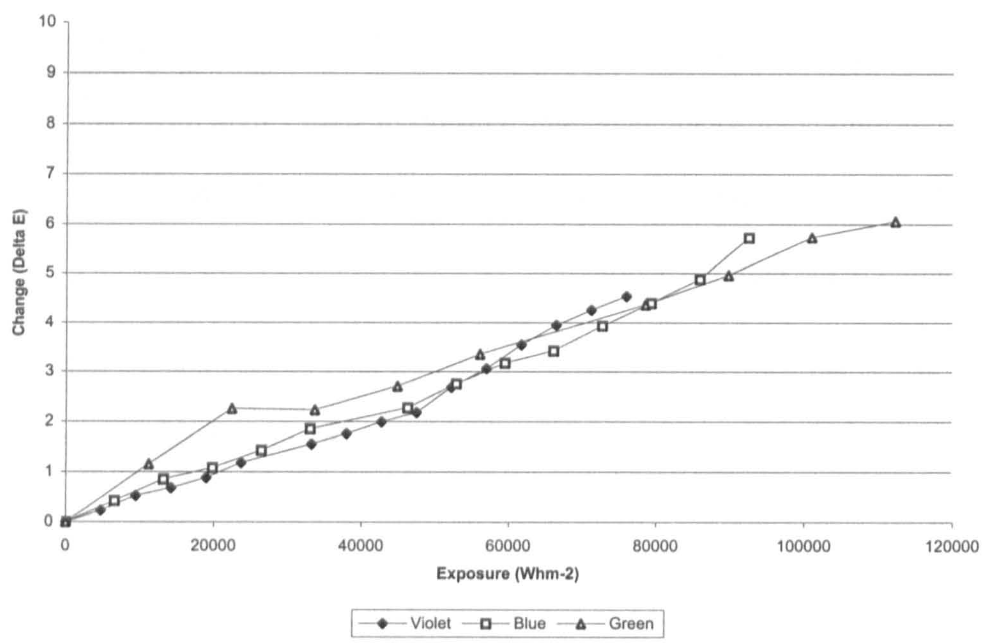

Fig 6.9 Plot showing the fading rate of blue printed patch from the Epson Pro 9000 ink set printed on Somerset Velvet paper (3.3) after exposure to the fluorescent light fastness tester with the violet, blue and green dichroic filters.

Generally, the violet and blue regions of the visible spectrum catalysed most of the fading reactions, except for the cyan ink patch samples 3.3 and 3.5, where the wavelengths transmitted by the yellow and orange filters caused the most rapid fading rates. This effect was also found by Saunders *et al.* (1994) for a selection of blue pigments and blue wool standards exposed under selective wavelengths[5]. Examination of the spectral characteristics of the 3.3 and 3.5 cyan inks indicates no particular difference in the spectral reflectance curves of these inks compared to the other cyan patches on samples 3.2 and 3.4, that fade faster under the violet and blue filters (see Appendix L (pp. L – 465, L – 470, L – 476, L - 481)). However, the fading rate of the cyan inks was overall irregular due to the presence of photochromatic reactions of the dye. Therefore, assessment of the effect of the colour filters for these samples could not be generalised.

Ink patches such as the 3.4 cyan, the 3.3 and 3.4 magenta, the 3.3 and 3.4 red and green, 3.4 blue, and the 3.4 grey scale composed of the CMYK inks printed at 50 % concentration showed a sudden increase in their fading rates during the test when exposed under the violet and occasionally blue dichroic filters (see fig. 6.3). Fading rates that accelerate with time are often caused by the continual break down of colourant particles (Giles *et al.*, 1980, Allen, 1991) (see 6.2.5).

Some of the ink patches showed the most rapid fading rates on exposure to the light transmitted by the green dichroic filter. This behaviour occurred on the grey scale ink patches composed from the CMY or CMYK inks printed at 25 % or 50 % ink concentrations produced on the uncoated Somerset Velvet (3.3) and Whatman (3.4) papers, and the cyan ink from the Iris 1.1 sample set. The wavelengths transmitted by this filter were not only from the green region of the visible spectrum (see table 6.4 and fig. 4.1) and included wavelengths from 400 nm to 570 nm. The rapid fading rates under the green filter, therefore, is due to the absorption characteristics of these patches, the region of wavelengths transmitted by these filters and the sensitivity of these patches to the wavelengths transmitted and absorbed.

The inks identified as being very sensitive to light in the previous light tests (Iris Morgan FA black and the Epson Pro 9000 magenta), exhibited rapid fading rates under all of the dichroic filters tested (see fig 6.10). Therefore, these inks have an overall sensitivity to the majority of wavelengths in the visible region of the spectrum; which is why these inks were shown to be the most sensitive to light.

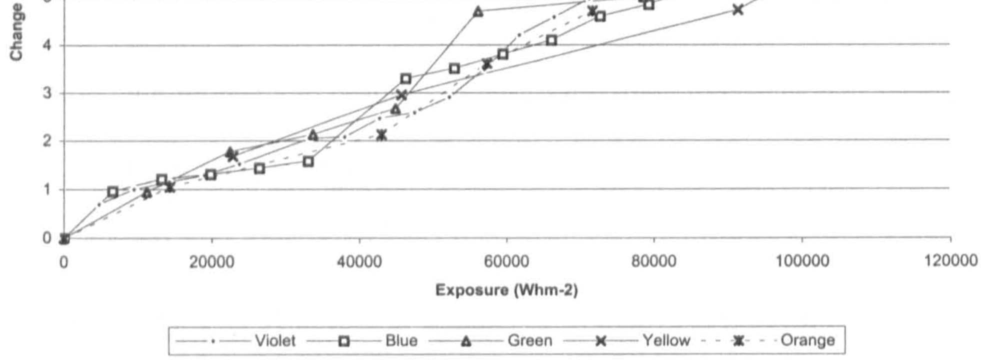

Fig. 6.10 Plot showing the change in ΔE_{ab} against exposure of the black ink patch from Iris ink set printed on Somerset Velvet paper (1.1) after exposure to the full range of dichroic filters employed.

6.2.8 The different light ageing conditions

Analysis of the ΔE_{ab} results collected from the CMYK printing ink samples that were exposed to the different light sources showed that the specific spectral distribution of the lamps could increase or decrease the fading rate of some of the inks according to their absorption spectra. In particular, the Epson Pro 9000 samples exposed to the halogen lamp showed that the cyan ink faded considerably more rapidly under this testing environment when compared to the other light sources. The tungsten-halogen lamp has a colour temperature of 3400 °K which means that it emits strongly in the orange/yellow portion of the spectrum (see 6.2.8.3).

For a majority of the inks, however, and particularly the colourants identified to be very sensitive to light, the different light sources produced very similar fading rates. The Microscal Light Fastness Tester, however, was considered the least reliable test method (see 6.2.8.1).

6.2.8.1 Microscal light fastness tester

Both the Microscal Light Fastness testers employed in this research were not ideal. The illuminance levels of both lamps varied around their circumference, relative humidity within the cooling cells could not be monitored and the reciprocity principle was not followed according to the results published by Saunders *et al.* (1994). The testers also operate at high temperatures of 40 °C for the MB/U (Mark 1C R/F) lamp and a 60 °C for the MBF/U (Mark IV) lamp. These accelerated temperature conditions can also contribute to the photochemical reactions, leading to increased fading rates[6], and deepening of the colourants. A slight deepening of the magenta ink was observed on the Iris 1.1 and 1.2 print samples, which is a known occurrence caused by the decreased dye aggregation caused by heating during an exposure test. Subsequent cooling can restore the original colour (Whitemore, 2000). Comparing results from the Microscal Light Fastness Tester to natural daylight shows relatively good correlation, although some of the data collected from the Lyson samples exhibited differences.

The samples that were shown to be photochromatic in other light fastness tests did not exhibit photochromatic reactions after exposure in the Microscal light testers. This was probably due to the high irradiance emitted by the light source, causing a rapid fade rate, and would require more frequent colour measurements to be taken.

After all the light ageing tests were performed, the illuminance levels produced by the Microscal MB/U (Mark 1C R/F) testing lamp appeared to increase. This variability may be an indication of the change of the energy radiated by the lamp over time, or it may be due to the limitations of the ability to take the lux measurement from exactly the same position as the initial recording.

6.2.8.2 Natural daylight

The natural daylight tests were also not an ideal light testing method, mainly because the test was not reproducible. Samples were exposed without controlling the temperature, relative humidity, irradiance levels, UV radiation content, and without filtering out gaseous and airborne particulates. On hot sunny days, the intensity of daylight can produce illumination values above 10 000 lux, which could mean that the reciprocity principle is not followed. The reciprocity principle does not apply to high illumination levels, because the level of the surrounding oxygen required for the photochemical reactions is generally not sufficient (see 3.5.2). The test ran according to natural day/night cycles, though, which allowed for the oxygen levels in the surrounding area of the samples to replenish (Gillet *et al.*, 2000). In addition, the samples were not ventilated, so over heating could have occurred[7]. The samples light aged with natural daylight show a rapid fading of the colourant at the beginning of the test. This type of behaviour signifies the rapid initial breaking of the weaker bonded smaller molecules at the surface of the dye[8].

6.2.8.3 Tungsten-halogen light ageing

The environmental conditions of the tungsten-halogen light test were not controlled. Therefore, the experiment could not be said to be reproducible. The tungsten-halogen light had a much lower illuminance level than all of the other tests, which enabled the measurement of the initial fading reactions of a selection of the samples to be made.

All of the ink samples from the Epson Pro 9000 samples set printed on Photo Glossy paper (3.1) showed a dormant phase at the beginning of the exposure period, where there was no apparent fading of the colourant. After approximately 500 - 700 lux-hours, the ink patches would then undergo photochemical reactions with measurable ΔE_{ab} values recorded. The samples from the Iris Morgan FA ink set printed on the Somerset and Whatman papers (1.1 and 1.2) did not show a dormant phase and underwent a degree of colour change after an initial exposure to light. The black ink in particular showed a rapid fading rate immediately on exposure to the tungsten-halogen light source. This behaviour signifies that this ink is particular sensitivity to light, and exhibition of a print produced with this type of ink should be considered with extreme caution.

The cyan ink from the Epson Pro 9000 ink set printed on Epson Photo Glossy paper (3.1) showed a more rapid fading rate under the tungsten-halogen lamp test than with the natural daylight, Microscal or Fluorescent light tests (see figs. 6.11, 6.12 and 6.13). This fading reaction has been reported by Wilhelm *et al.* (1994) with the fading of colour photographs and Saunders *et al.* (1994) with the fading of artist's pigments. With natural daylight, Microscal and fluorescent light tests, the magenta ink was shown to be the most sensitive ink out of this ink set. Under daylight illumination, the initial fading rate of the yellow ink was faster than observed with the fluorescent illumination, and the cyan ink was shown to be the least light sensitive compared to the other inks from this ink set. This behaviour is attributed to the spectral distribution of this light source, which has a colour temperature of 3400 °K, and emits light strongly in the yellow/orange region of the spectrum. Analysis of the reflectance spectra of the cyan ink patch shows that the ink absorbs strongly in this region. Therefore, these wavelength bands are responsible for a considerable amount of the photochemical reactions taking place. A photochromatic reaction was observed for the yellow ink from the Epson Pro 9000 ink set printed on Epson Photo glossy paper (3.1). This effect was most obvious on the patches printed at 50 % and 25 % ink concentrations.

Measurement of the test environment showed that there was a certain degree of variation of temperature and relative humidity on hot humid days, but analysis of the ΔE_{ab} results did not show any influence of the environmental changes.

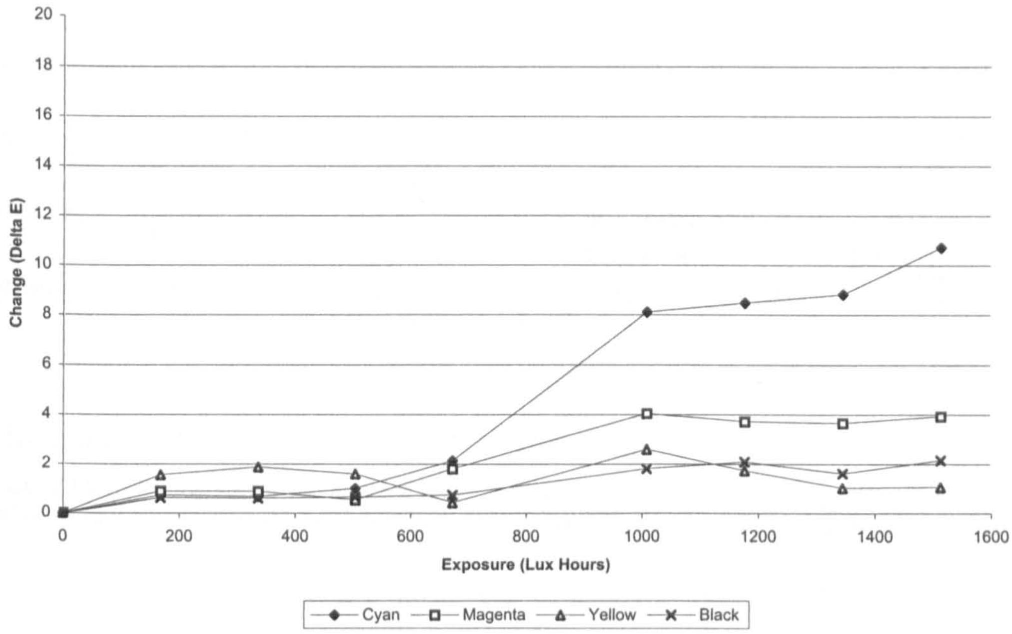

Fig. 6.11 Plot showing the change in ΔE_{ab} of the CMYK ink patches from Epson Pro 9000 ink jet printed on Photo Glossy paper (3.1) after exposure to the tungsten-halogen light fastness tester.

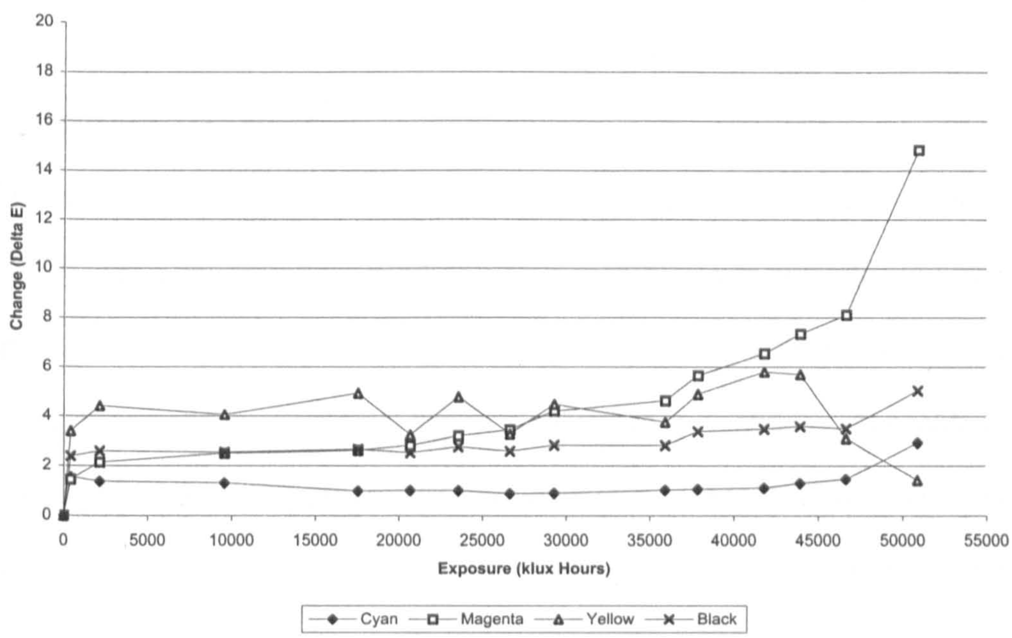

Fig. 6.12 Plot showing the change in ΔE_{ab} of the CMYK ink patches from Epson Pro 9000 ink jet printed on Photo Glossy paper (3.1) after exposure to the natural daylight light fastness test.

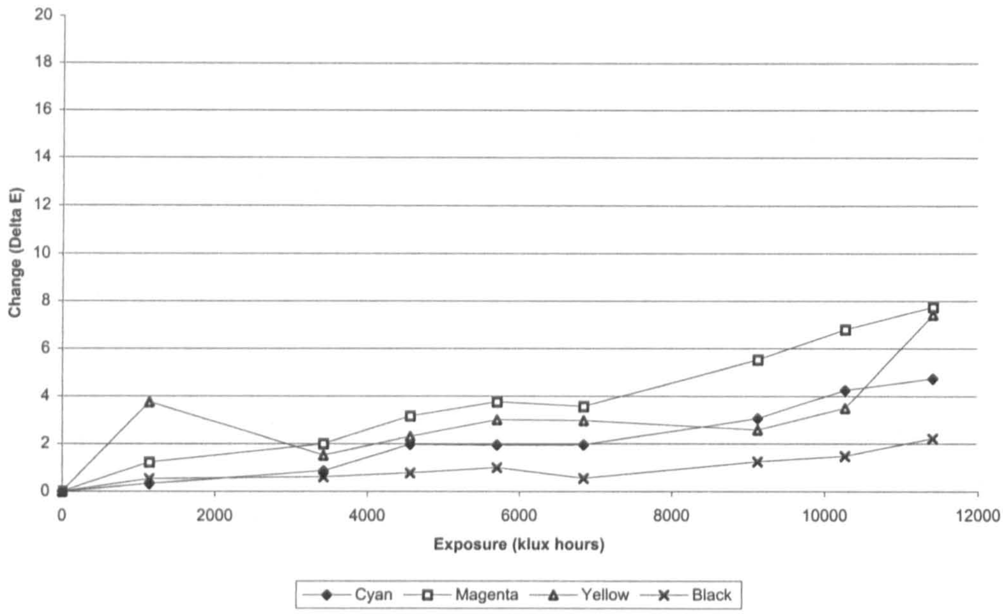

Fig. 6.13 Plot showing the change in ΔE_{ab} of the CMYK ink patches from Epson Pro 9000 ink jet printed on Photo Glossy paper (3.1) after exposure to the fluorescent light fastness tester with the UV filter.

6.2.8.4 Fluorescent light ageing

The fluorescent light test allowed for the greatest control of relative humidity and temperature compared to the other test conditions investigated, but this system still had inherent problems. After the samples were removed for colour measurement, which occurred once a week, the relative humidity of the housing would drop by approximately 10 %. It would take over six hours for relative humidity in the box to reach the desired level. The temperature of the box remained unaffected and stayed close to room temperature.

After testing, it was realised that the air inside the box should have been circulated, to prevent the depletion of oxygen near the surface of the test samples. The box was not 100 % airtight and the opening of the box once a week allowed for the air to be replenished, but future testing should incorporate this function to make sure that the amount of oxygen is close to that in the ambient normal atmosphere.

6.2.9 Blue wool standards

Blue wool scales were employed in this study to compare the light aged print samples with a known fading standard, and to monitor the fading rate produced by light source in different positions within the exposure area. The blue wool scale is designed for daylight or artificial daylight exposures only, and is not suitable for fluorescent or halogen-tungsten light exposures (see 4.3.8). Therefore, blue wool scale ratings were only allocated to the samples light aged under natural daylight and the Microscal Light Fastness Tester. With the fluorescent, tungsten-halogen and Microscal tests, the blue wool scales were employed to measure the consistency of the light source.

Previous studies of the blue wool scale have shown that there are inconsistencies with the fading rates of some of the dyes. Jaeckel *et al.* (1963) commented that "*spacing of standards as a whole is irregular.*"[9], and Rawlands (1963) concluded from a study into the performance of the blue wool scales under natural daylight that "*From a consideration of our results, it appears that there is a considerable variation in performance according to when exposure began. This variation could not be explained by humidity conditions*"[10]. The fading rate of the blue wool scales in this light investigation also showed that the scales were not uniform, for all of the light exposures tested.

For the Microscal Light Fastness Tester, one set of blue wool scales 1 to 4 was placed in a cooling cell at different locations around the perimeter of the tester for each sample set exposed (see 4.4.1). Analysis of the ΔE_{ab} values of the blue wool scales after exposure to the tester for one week revealed that there was discontinuity between the fading rates of each of the blue wool scales. The scales faded at different rates at the various locations around the lamp. The following table lists the mean, standard deviation and percentage difference between the ΔE_{ab} results after one week's exposure.

Table 6.5 Fading changes of blue wool scale dyeings 1-4 after exposure to the Microscal tester after 7,340 klux hours.

Location around perimeter of Tester	*Blue Wool Scales* 1	2	3	4
1	53.77	46.90	27.63	6.32
2	52.58	49.51	37.80	8.31
3	50.16	49.55	37.50	8.33
4	53.26	45.80	10.79	18.55
5	48.37	41.77	22.71	4.60
6	48.50	42.83	26.85	5.68
7	53.67	47.73	27.82	6.16
8	49.54	43.35	28.11	6.01
9	50.24	44.76	27.97	6.21
Mean	51.12	45.80	27.47	7.80
Standard Deviation	2.20	2.85	7.98	4.21
Percentage Difference between the scales (%)	-	10.41	40.02	71.61

The following graphs show the fading rate for blue wool scales 1 to 7 exposed under natural daylight test conditions, with and without an UV filter.

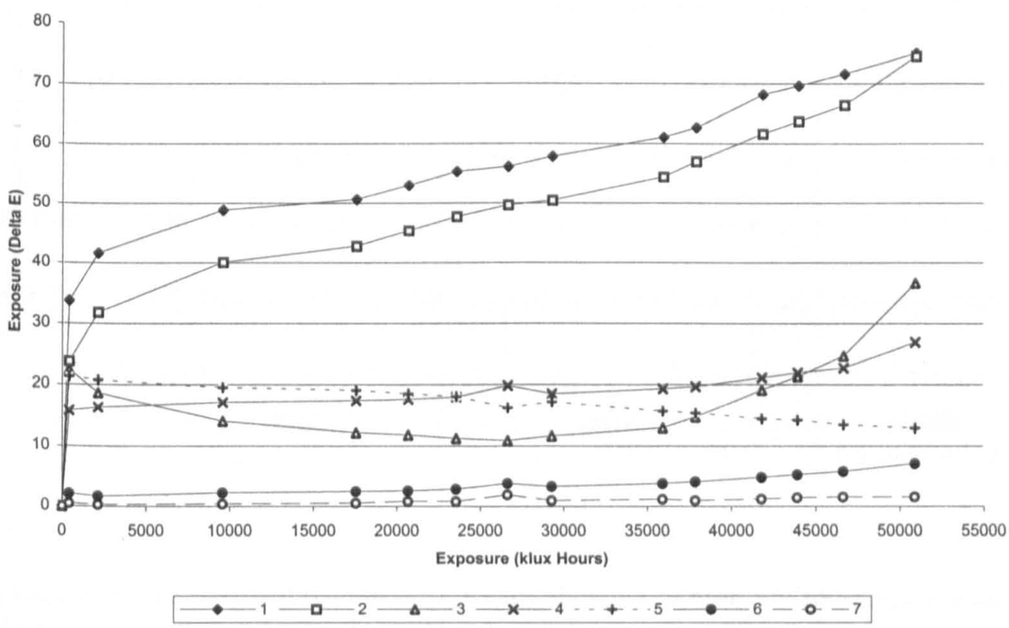

Fig. 6.14 Plot showing the fading rate of blue wool scales one to seven after exposure to the natural daylight light fastness tests unfiltered.

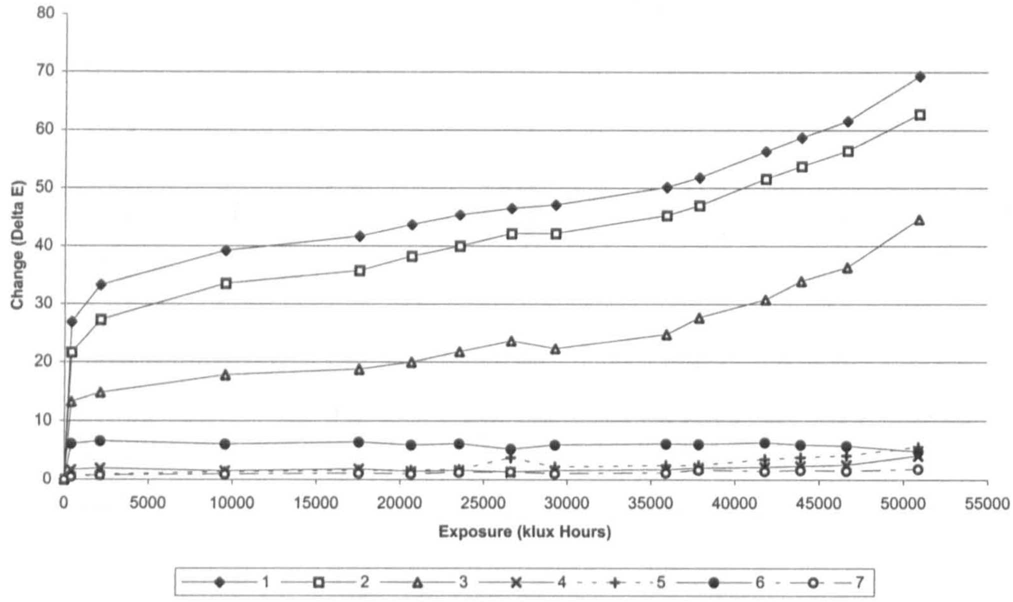

Fig. 6.15 Plot showing the fading rate of blue wool scales one to seven after exposure to natural daylight with a UV filter.

The results in figs. 6.14, 6.15, 6.16 and 6.17 show there is also no regularity between the fading rate of each of the blue wool scales for both of the exposures. When plotted against the logarithm of exposure time as suggested by Feller (1978), the fading rates of blue wool scales exposed to natural daylight still do not correlate (see Appendix H (p. H - 382)). The results for the blue wool dyeings exposed with the UV filter show much more consistency than the dyeings left unfiltered. From the unfiltered exposure, the blue wool scale number 3 fades at a lesser rate than blue wool number 4 and 5. Jaeckle *et al.* (1966) found "*that each standard is in fact faster than its next lower neighbour on the straight line approximation by 2 ½ to 3 times*"[11].

The variations of the blue wool scale exposed to the Microscal Light Fastness Tester could be due to the discrepancies found for the amount of light radiated by the lamp and the UV output, since the UV filter has made a significant difference with the natural daylight exposures. Other independent critical investigations into the fading rates of the blue wool scale all give different conclusion for each of the dyeings. The variation in results could be due to different depths of dyeing for the scales and other environmental factors such as temperature and humidity as suggested by Rawlands (1966). Jaeckal *et al.* (1963) also found that the scales faded differently between seasons showing a more rapid fade in the autumn than the spring, and attribute the results to variations in the UV content of daylight.

The blue wool dyeings exposed to the fluorescent and tungsten-halogen tests showed slight differences in fading rate at the different positions around the testers. With both the fluorescent and tungsten-halogen light tests, the location of the samples was circulated around the tester so any differences in lux levels should have been compensated.

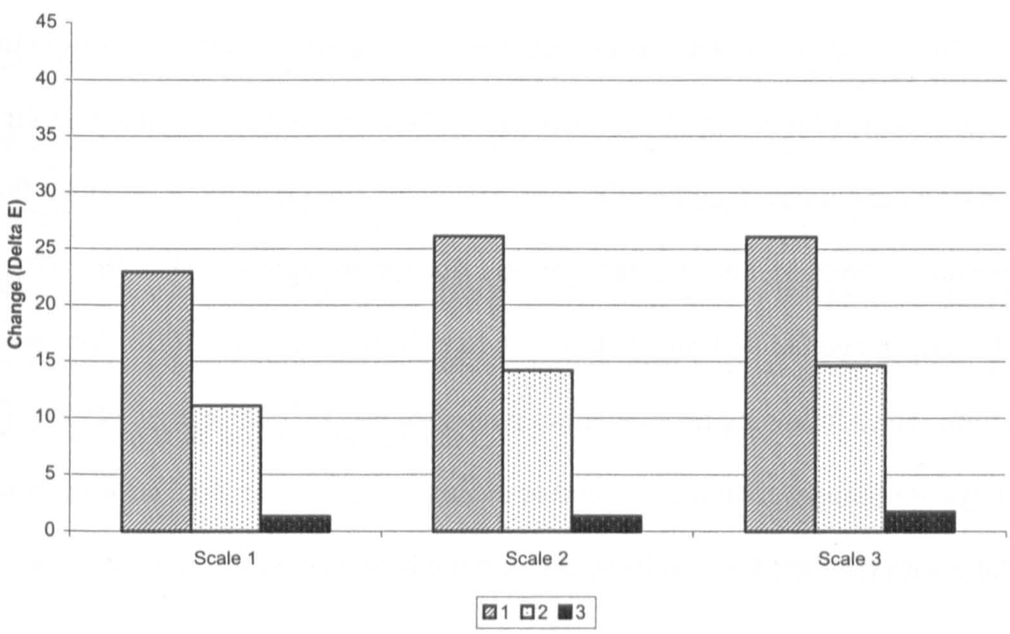

Fig. 6.16 Change in ΔE_{ab} of blue wool scale dyeings 1-3 after exposure to the tungsten-halogen light fastness tester after 1,512 lux hours.

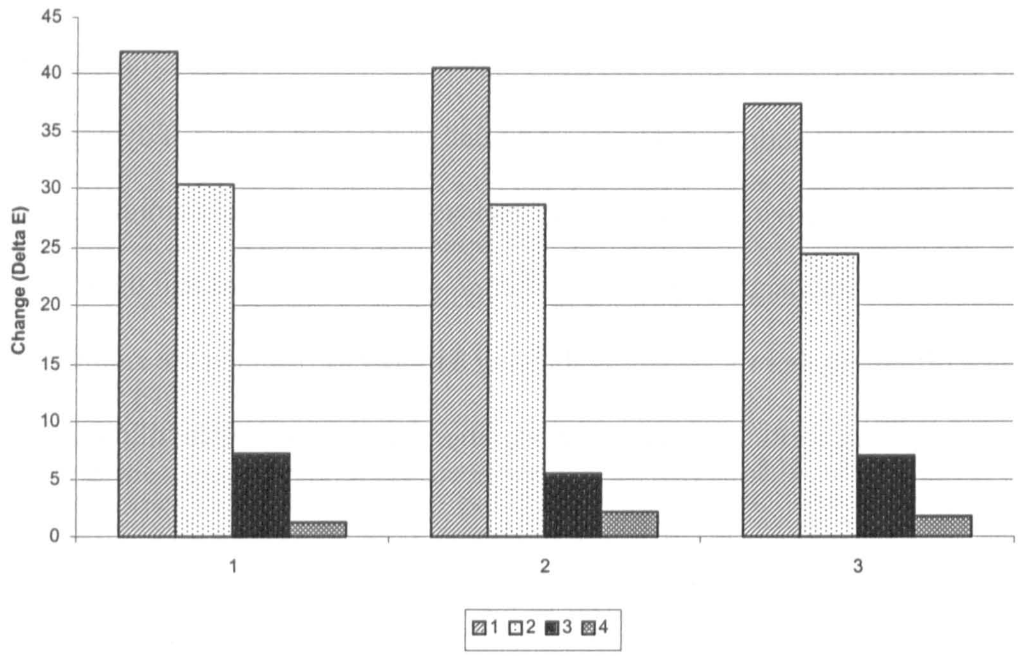

Fig. 6.17 Change in ΔE_{ab} of blue wool scale dyeings 1-3 after exposure to the fluorescent light fastness tester for 11,405 klux-hours.

6.2.10 Image fading limits

To establish the light fastness of a colourant a just noticeable fade (JNF) limit is used for the calculations and is usually taken as ΔE_{ab} of 2.0 units (equivalent to the grey scale 4) (Pretzel, 2000) (also see 4.3.7). This criterion was adopted for this study and image fading limits were calculated from the results obtained from the natural daylight, tungsten-halogen and fluorescent light fast tests (see table 6.6). The image fading limits in table 6.6 have been given a BS 1006 Grey Scale (1990) rating following the guidelines published by Derbyshire *et al.* (1999). The image life limits were not compared or evaluated to the blue wool scales exposed along with the light fastness tests, because the blue wool scales did not show regular spacing of the standards in all of the tests (see 6.2.9).

It was noticed that a ΔE_{ab} of 2.0 was less obvious on the yellow ink samples than on the other colourants. The yellow ink on some of the print samples tested did not visibly exhibit a JNF compared to the control, even though the calculated change in ΔE_{ab} was over 2.0. Instead, a slight fade was perceptible between the values of $\Delta E_{ab} = 2.5 - 3.0$. Published literature on this occurrence concludes that the inaccuracy of the CIELAB colour space and the ΔE_{ab} measurement is responsible for the breakdown of the relationship between colour measurement and perceptible change (Gilchrist *at al.*, 1999)[12].

However, since there was only one viewer to observe and recorded perceptible difference, less weighting was placed on this value due to the subjectivity of the measurement. All lux hour limits, therefore, were calculated using the ΔE_{ab} measurement, but a possible variation is this result has been acknowledged. Previously published literature has discussed the introduction of more accurate equations to overcome this problem in the future (see 4.3.6).

It was realised that investigating the fading rate of the discrete patches of colour does not show how the light sensitivity of an ink affects the overall colour balance of a printed image. Wilhelm *et al.* (1994) have discussed this occurrence in photography, where many images undergo a change in colour balance. He goes on to say that this is more noticeable with memory colours such as grass, tarmac, blue sky, skin tone fruit and vegetables, etc[13].

Table 6.6 Approximate exposure times until just noticeable fade (JNF) occurs. Results calculated by interpolation of the graphs produced from the natural daylight, tungsten-halogen and fluorescent exposures. One JNF represents a ΔE_{ab} of 2, which is equivalent to the grey scale 4 (Smith, 1997, Pretzel, 2000). The 'years of display' published by Wilhelm (1999) are calculated until noticeable fading occurs, which represents a density change of 0.3 %.

Sample No.	*Approximate klux hours until one JNF occurs x under different light exposures (ink colour with most rapid fading rate)*			*Assigned ISO level following data derived by Michalski (1990) (see table 6.7)*	*Effect of ink concentration and combination on the fading rate (data obtained from Microscal and fluorescent exposures)*	*Recommended exposure level (50 lux @ 8 lux hours per day) (yrs.)*	*Wilhelm's recommended 'years for display' (450 @ 12 hours per day (1999))*	
	Natural Daylight	*Tungsten-halogen*	*Fluorescent*				*This study*	*Wilhelm*
1.1	Less than 400 (K)	160 (K)	Less than 852 (K)	1	Fading rate increased by ΔE_{ab} of 2 units with ink mixtures; fading rate of black ink increases by ΔE_{ab} of 6 units at 75 % ink concentration; yellow ink increases by 5 units at 75 % ink concentration.	1	1-2	Not tested months
1.2	Less than 400 (K) (K)	Less than 160 (K)	Less than 852	1	Fading rate increased by ΔE_{ab} of 2 units with ink mixtures; fading rate of black ink increases by ΔE_{ab} of 8 units at 75 % ink concentration; yellow ink increases by 10 units at 50 % ink concentration.	Less than 1	Less than 1	Less than 1 month
2.1	Less than 400 (Y)	Not tested.	Not tested.	1	Not tested.	Less than 3	1-2	Not tested months

Table 6.6 continued

Sample No.	*Approximate klux hours until one JNF occurs x under different light exposures (ink colour with most rapid fading rate)*			*Assigned ISO level following data derived by Michalski (1990) (see table 6.7)*	*Effect of ink concentration and combination on the fadingrate (data obtained from Microscal and fluorescent exposures)*	*Recommended exposure level (50 lux @ 8 lux hours per day) (yrs.)*	*Wilhelm's recommended 'years for display' (450 @ 12 hours per day (1999))*	
	Natural Daylight	*Tungsten-halogen*	*Fluorescent*				*This study*	*Wilhelm*
2.2	Less than 400 (K)	Not tested.	Not tested.	1	Fading rate increased by ΔE_{ab} of 0.7 units with ink mixtures; fading rate of magenta ink increases by ΔE_{ab} of 25 units at 50 % ink concentration; the yellow ink increases by ΔE_{ab} of 15 units at 75 % and 50 % ink concentration; fading rate of magenta ink increases by ΔE_{ab} of 20 units at 75 % and 50 % ink concentration	Less than 3	1-2 months	Not tested
2.3	16,000 (Y)	Not tested.	Not tested.	4-5	Not tested.	110	8	Not tested
2.4	1,500 (K)	Not tested.	Not tested.	2-3	Fading rate increased by ΔE_{ab} of 10 units with ink mixtures; fading rate of black ink increases by ΔE_{ab} of 7-8 units at 25 % ink concentration.	10	9-10 months	Not tested
3.1	Less than 400 (Y)	336 (Y)	Less than 852 (Y)	1	Slight increase in fading of ink 2 mixtures by ΔE_{ab} of 0.5 units.		2-3 months	Not tested

Table 6.6 Continued

Sample No.	*Approximate klux hours until one JNF occurs x under different light exposures (ink colour with most rapid fading rate)*			*Assigned ISO level following data derived by Michalski (1990) (see table 6.7)*	*Effect of ink concentration and combination on the fadingrate (data obtained from Microscal and fluorescent exposures)*	*Recommended exposure level (50 lux @ 8 lux hours per day) (yrs.)*	*Wilhelm's recommended 'years for display' (450 @ 12 hours per day (1999 (1999))*	
	Natural Daylight	*Tungsten-halogen*	*Fluorescent*				*This study*	*Wilhelm*
3.2	Less than 400 (M)	Less than 160 (C)	Less than 1,704 (K)	1	Fading rate increased by ΔE_{ab} of 26 units with ink mixtures; fading rate of black ink increases by ΔE_{ab} of 10 units at 75 % ink concentration; magenta ink increases by 28 units at 75 % ink concentration.	Less than 1	1-2 months	Not tested
3.3	Not tested.	Not tested.	Less than 852 (C)	1-2	Fading rate increased by ΔE_{ab} of 9 units with ink mixtures; fading rate of black ink increases by ΔE_{ab} of 16 units at 50 % ink concentration; magenta ink increases by 7 units at 50 % ink concentration.	3	4-5 months	Not tested

Table 6.6 Continued

Sample No.	*Approximate klux hours until one JNF occurs x under different light exposures (ink colour with most rapid fading rate)*			*Assigned ISO level following data derived by Michalski (1990) (see table 6.7)*	*Effect of ink concentration and combination on the fadingrate (data obtained from Microscal and fluorescent exposures)*	*Recommended exposure level (50 lux @ 8 lux hours per day) (yrs.)*	*Wilhelm's recommended 'years for display' (450 @ 12 hours per day (1999))*	
	Natural Daylight	*Tungsten-halogen*	*Fluorescent*				*This study*	*Wilhelm*
3.4	Less than 400 (C)	Not tested.	Less than 852 (C)	1	Fading rate increased by ΔE_{ab} of 8 units with ink mixtures; fading rate of black ink increases by ΔE_{ab} of 16 units at 50 % ink concentration. Magenta ink increases by 8 units at 50 % ink concentration.	Less than 3	2-3	Not tested
3.5	Not tested.	Not tested.	Less than 2,556 (Y)	2-3	Fading rate increased by ΔE_{ab} *of* 14 units with ink mixtures; fading rate of black ink increases by ΔE_{ab} of 8 units at 75 % ink concentration. Magenta ink increases by 10 units at 50 % ink concentration.	8-15	1	Not tested
3.6	Less than 400 (Y)	Not tested.	Not tested.	1	Fading rate increased by ΔE_{ab} of 1 unit with ink mixtures; fading rate of black ink increased by ΔE_{ab} of 3 units at 75 % ink concentration.	Less than 3	2-3	6 – 7 months

Table 6.6 Continued

Sample No.	*Approximate klux hours until one JNF occurs x under different light exposures (ink colour with most rapid fading rate)*			*Assigned ISO level following data derived by Michalski (1990) (see table 6.7)*	*Effect of ink concentration and combination on the fadingrate (data obtained from Microscal and fluorescent exposures)*	*Recommended exposure level (50 lux @ 8 lux hours per day) (yrs.)*	*Wilhelm's recommended 'years for display' (450 @ 12 hours per day (1999))*	
	Natural Daylight	*Tungsten-halogen*	*Fluorescent*				*This study*	*Wilhelm*
4.1	2,200 (M)	Not tested.	Not tested.	2-3	Blue; 100% Y 50% K; showed slight increased fading of 1 ΔE_{ab} unit; the fading rate of the black ink increased by ΔE_{ab} of 2 units at 75 % ink concentration.	15	1	5
5.1	47,500 (Y)	Not tested.	Not tested.	5-6	No change.	325	24	Not tested
5.2	23,000 (Y)	Not tested.	Not tested.	4-5	Not tested.	158	12	Not tested
5.3	9,500 (M)	Not tested.	Not tested.	3-4	No catalytic fading occurred with the toners, but the fading rate of the yellow ink increased by by ΔE_{ab} of 18 units at 50 % ink concentration; the magenta ink increased by ΔE_{ab} of 2 units at 75 % ink concentration	65	5	Not tested
5.4	38,000 (M)	Not tested.	Not tested.	5-6	Not tested.	260	19	Not tested
5.5	38,000 (M)	Not tested.	Not tested.	5-6	Not tested.	260	19	Not tested

Table 6.7 The amount of exposure in *million lux hours to cause one JNF*. Assumes no UV radiation. Data derived from Michalski 1990 (Derbyshire *et al.*, 1999).

ISO Level	1	2	3	4	5	6	7	8
Million lux hours to cause one JNF	0.4	1.2	3.6	10	32	100	300	900
Categories	Category A Sensitive			Category B Intermediate			Category C Durable	

6.3 Inverse relationship of colour gamut and light stability of the print materials

The inverse relationship between light fastness and colour gamut was not evident with the samples examined in this investigation. The ink sets that were tested on different types of coated and uncoated papers (Lyson and Epson samples), all showed lower light fastness values on the uncoated papers (Inveresk Somerset Velvet and Whatman Watercolour), compared to the same ink printed on the coated papers (Epson Photo Glossy, Presentation Matt or Lyson Soft and Rough Fine Art). The samples printed on the uncoated papers, however, had much smaller colour gamuts than the samples printed on the coated papers, therefore, dispelling the inverse relationship theory. The inverse relationship did apply to the electrophotographic samples compared to the ink jet printed materials. Examination of the colour gamut of the Canon print samples showed that the gamut was smaller than the colour range of the ink jet printed samples produced on the coated papers, and the Canon toners had the better light fastness ratings overall than the ink jet printed samples.

6.4 Discolouration of the digital print papers

All of the coated ink jet and the electrophotographic papers showed a tendency for the coating/paper to yellow on exposure to light. The Canon electrophotographic papers yellowed considerably, leading to colour change with some of the print samples, especially the patches that were printed at lower toner concentrations.

After thermal ageing, all the papers employed in this investigation discoloured, including the high quality Somerset and Whatman uncoated papers. The Somerset

Velvet paper showed the least amount of discolouration, but the Whatman watercolour paper demonstrated a high degree of yellowing; which was not expected since this paper is composed of good quality cotton rag. The pH value of the paper changed from 8.3 to 6.2, therefore, the paper contains substances that turn the paper acidic over time.

Some of the coated papers were found to be acidic and became more acidic on ageing. Literature published on the composition of ink jet inks and papers discuss the manipulation of the pH value of the papers to improve the drying and wet fastness of the liquid ink once it is printed onto the paper (see 3.2.5). The ink contains dyes that are liquid in an alkaline solution but once printed they become solid on an acidic substrate. These characteristics were evident for the following papers:

- Epson Pro 9000 Photo Glossy, 190 gsm
- Epson Photo Stylus Photo Glossy, 141 gsm
- HP Heavy Weight Coated Matt, 130 gsm

Overall, the coated ink jet papers showed similar amounts of discolouration after thermal ageing. Generally, the coated side of the paper discoloured further than the uncoated fibre based verso. Discolouration of the coating is attributed to the presence of fluorescent agents and latex in the surface formulations. Under UV light all of the coated papers, except for the Epson Photo Stylus Glossy paper, fluoresed blue, indicating the presence of fluorescent whitening agents. The Epson Photo Stylus Glossy paper was the only coated substrate to show a higher level of discolouration on the verso than the recto. This paper is composed of three layers with an ink receiving coating, fibre based middle layer and plastic type base, and was the only paper to have a plastic type base.

6.5 Conservation

Nearly all of the ink jet inks showed extreme sensitivity to all of the wet treatments investigated. This includes all wash treatments, de-acidification agents, solvents and humidification. Some of the inks were even sensitive to the water-based wheat starch paste used for tear repair, this occurred with the Iris and Lyson ink sets printed on the uncoated papers. The Lyson Lysonic ink printed on the matched Lyson Soft Fine Art paper was the only ink jet ink that was shown not to be affected by the wash treatments, but the magenta ink was sensitive to the calcium hydroxide de-acidifying treatment. All of the Canon electrophotographic print samples showed no change with the wash treatments, but the black toner from the 5.4 and 5.5 sample sets was fugitive with industrial methylated spirits (IMS), and the spot tests using a de-acidifying agent caused water staining on the toners. Previous research has found that uneven wetting occurred with the washing of electrophotographic print material (Norville-Day, 1994). This result was not observed with the samples tested in this investigation, but they were relatively small (50 mm x 140 mm) and the printed patches also covered a small area (20 mm x 40 mm). Therefore, uneven wetting could occur with larger printed materials.

The magenta ink from the Epson Pro 9000 ink set under went a colour change with the calcium hydroxide de-acidifying treatment. The ink changed from magenta to orange on all the sample sets tested using different types of paper, showing that the dye is pH sensitive. Generally, de-acidification is not recommended for ink jet prints because differential solubility can be used with the formulation of the inks and papers, where the pH value of the ink jet papers and inks are manipulated to improve the wet fastness of the printed output (see 3.2.5)

Mechanical dry cleaning did not appear to have affect any of the papers investigated. In practice, this treatment would never be used on image region, but tests showed that the inks could be damaged if care was not taken with this process, especially with the ink jet ink printed on uncoated papers.

The tear repair of ink jet coated and electrophotographic papers was successful, with the coated papers adhering well with the wheat starch paste, but some of the ink jet inks were affected by the moisture introduced by the paste, which lead to some loss of the colourant onto the papers used for pressing the repair.

6.6 Identification

Overall, identification of the type of ink jet or electrophotographic prints is extremely difficult, with the vast variety of printers and inks available on the market. From the selection of prints tested the original ink jet coated papers can be identified under a combination of ambient light, UV light, and magnification. Most of the coatings tended to fluoresce blue light under fluorescent light due to the presence of fluorescent agents in the coatings, however, this did not occur with all of the coated papers such as the Epson Photo Stylus Photo Glossy paper. The difference between a gloss and a matt-coated paper can be distinguished under a combination of ambient light, raking light and magnification. The type of base the coated paper consists of can also be identified using transmitted light. The new 'fine art' coated papers are much harder to identify, but examination of the saturation of the inks, especially the magenta and black inks, and the regularity of the ink jet dots and absence of wicking may give an indication of whether a paper that appears to be uncoated does indeed contain a coating.

The variable dot size of the CIJ Iris prints was visible under magnification (X 10), whereas the droplets from the other DOD processes (Epson, Hewlett Packard and Lyson) all exhibited dots of uniform size. This visual characteristic could aid with the identification of a continuous tone ink jet process, but comparisons with other ink jet processes needs to be performed to confirm this statement.

Only two different digital printing processes were examined in this study. Therefore, identification of these two processes compared to other printing methods was not established.

6.7 Paper composition

The X-ray spectrometer graphs revealed that the coatings on the Epson Photo Glossy and Presentation Matt papers were composed of silica, oxygen, carbon, aluminium and chlorine. The Photo Glossy paper also contained magnesium. Analysis of the supporting substrate also showed that the paper had the same composition and that the Presentation Matt paper contained magnesium in the substrate base only. The presence of silicon, water and carbon was as expected from the information published in the literature on the composition of ink jet coated papers (see 3.2.4.2). Chlorine is used often used to bleach paper, and its presence can produce an acidic pH value. Compounds of magnesium can be used as fillers, and the presence of aluminium suggests that alumina has been used as a pigment (see 3.2.4.2).

SEM photographs of the cross-section of the Epson papers showed that the coating on the Photo Glossy paper appears to have been diffused into the supporting substrate, as the coating layer has seeped into the fibre base. Whereas the coating on the Presentation Matt paper were shown to lie on top of the paper base. The coatings on both papers exhibited good mechanical strength.

The Canon papers were both found to contain lignin, which can explain the rapid yellowing of the paper in both the light fastness and thermal/dark ageing tests. The presence of lignin in the paper signifies that these materials are not of archival quality and will become brittle and discoloured as the lignin content degrades in the presence of light and with age.

6.8 The overall performance of the print samples after testing

Table 6.8 Summary of results for the Iris printed samples

Test	*Results*
Light Fastness	The black ink from the Iris ink set proved to be extremely sensitive to light under all exposures. With the tungsten-halogen light test, which had a total exposure of 1,512 klux hours, the black ink produced a JNF after approximately 168 klux hours, and faded immediately on exposure to light. The black ink reacted by fading and changing colour turning to a pale orange after a prolonged period of exposure. Thin layer chromatography showed that this ink and all of the other black ink jet inks tested in this study were composed of a violet/dark blue and orange/yellow dye[14]. The yellow ink from the Iris ink set was also very sensitive to light fading to a lighter tone. Both the magenta and cyan inks had relatively good light fastness rates under all of the test exposures.
Estimated exposure until JNF occurs (klux hours).	Sample 1.1 – 160 – 170, Sample 1.2 – 150 – 170.
Effect of Paper Substrate	Under different light exposures the cyan and yellow inks showed better light fastness when printed on the Whatman paper compared to the same inks produced on the uncoated Somerset paper. The black ink showed slightly better light fastness when printed on the Somerset paper. On exposure to the tungsten-halogen tests all of the inks exhibited better light fastness on the Somerset paper, compared to the Whatman paper samples.
Catalytic Fading	Combinations of the most light sensitive inks, the yellow and black, produced the highest fading rate out of all of the colour patches tested.
Ink Concentration	Ink concentration was shown to be of significance with all of the inks demonstrating more rapid fading at 75 % and 50 % ink concentrations.
Presence of Erratic Fading Rates	The cyan, yellow and magenta inks produced erratic fading rates when exposed under the violet and blue dichroic filters. The magenta ink printed on the Whatman paper also produced irregular fading rates on exposure to the green, yellow and orange dichroic filters.
Effect of UV Filter	Use of an UV filter made little difference to the fading rates of the black and yellow inks under the natural daylight test, but the magenta and cyan inks showed no visible signs of change after exposure with the filter. Overall, the improvement was between 42 % – 53 %.
Effect of Dichroic Filters	All of the inks exhibited more rapid fading on exposure to the violet and blue dichroic filters.

Table 6.8 continued

Test	*Results*
Conservation Treatments	All of the inks were shown to be extremely sensitive to water therefore, conservation of this material should be undertaken with caution, as it will not tolerate any moisture. Exhibitions and storage of this material showed also be considered carefully as the inks are sensitive to high humidity conditions (80 % and above).
Identification	Under magnification (X 10), the variable dot size of the CIJ printing process is visible.
Thermal Ageing of Coated Papers	The uncoated Somerset and Whatman papers both yellowed slightly after thermal/dark ageing. The Whatman paper exhibited further discolouration than the Somerset paper. Both papers were alkaline. After thermal ageing the pH value of the Somerset paper fell to around neutral and the Whatman paper became slightly acidic.

Table 6.9 Summary of results for the Lyson printed samples

Test	*Results*
Light Fastness	The yellow ink was the most light sensitive colourant from the Lysonic ink set, and the black ink was the most light sensitive colourant from the Fotonic ink set.
Estimated exposure until JNF occurs (klux hours).	Sample 2.1 – Less than 400, Sample 2.2 – Less than 400, Sample 2.3 – 16,000, Sample 2.4 – 1,500.
Effect of Paper Substrate	Both ink sets were shown to be more light stable and wet fast when printed on the uncoated Whatman paper. When printed on their matched coated papers, the same ink sets showed to be significant more light sensitive. However, the inks showed better wet fastness when printed on the coated papers than when produced on the uncoated Whatman paper.
Catalytic Fading	Catalytic fading occurred when the yellow and magenta inks were printed with 50 % of the black ink with the Fotonic ink set, and when the magenta ink was printed with 50 % black with the Lysonic ink set.
Ink Concentration	Print concentration affected the light fastness results, with the inks generally fading at faster at 75 % and 50 % ink concentration. Only the black ink from the Lysonic ink set printed on Whatman paper showed a more rapid fading rate at 25 % ink concentration.
Presence of Erratic Fading Rates	The cyan ink from both ink sets exhibited erratic fading rates on exposure to light. Further testing showed that this ink was photochromatic.

Table 6.9 continued.

Test	*Results*
Effect of UV Filter	Use of an UV filter improved light fastness for all of the Lyson samples tested from 57 % – 75 %.
Effect of Dichroic Filters	Not tested.
Conservation Treatments	The Lysonic ink set printed on the coated SFA paper was not affected by any of the aqueous treatments tested. The Fotonic ink set printed on coated RFA paper was slightly fugitive to the aqueous treatments. Both ink sets printed on the uncoated papers were very fugitive to all of the wet treatments and were also sensitive to the moisture from the wheat starch paste used for tear repairs.
Identification	Uniformly sized droplet could be observed on the areas printed at low ink concentrations (25 % and 50 %), under magnification (X 10).
Thermal/Dark Ageing of Coated Papers	Both of the Lyson coated papers yellowed after thermal/dark ageing. The Rough Fine Art paper discoloured more than the Soft Fine Art paper by a difference of approximately ΔE_{ab} of 2. The yellowing was less pronounced on the uncoated side of the paper. Both papers were slightly alkaline and both pH values fell to around neutral after thermal ageing.

Table 6.10 Summary of results for the Epson printed samples

Test	*Results*
Light Fastness	The magenta from the Pro 9000 ink set was very sensitive to light, the black ink also quite light sensitive. The Epson Photo Stylus 870 print samples exhibited relatively good light fastness. The cyan and magenta inks showed to be the most sensitive to light from the ink set.
Estimated exposure until JNF occurs (klux hours).	Sample 3.1 – 336, Sample 3.2 – less than 1,704, Sample 3.3 – less than 852, Sample 3.4 – less than 400, Sample 3.5 – less than 2,556, Sample 3.6 – less than 400.
Effect of Paper Substrate	All of the Epson Pro 9000 inks tested showed better light fastness characteristics when printed on their match coated inkjet papers, compared to when printed on the uncoated papers and the ISVE.
Catalytic Fading	Catalytic fading of the dye mixtures occurred on all of the Epson samples tested on a variety of ink patches including, the 25 % and 50 % printed grey scales for all of the Epson Pro 9000 samples.

Table 6.10 continued.

Test	*Results*
Ink Concentration	Ink concentration affected the light fastness results, with the inks generally fading at faster at 75 % and 50 % ink concentration. Only the black ink from the Epson Pro 9000 ink set printed on Whatman paper showed more rapid fading at 25 % ink concentration.
Presence of Erratic Fading Rates	Both the cyan and yellow inks from the Epson Pro 9000 ink set printed on Presentation Matt paper, and the yellow inks printed on the Photo Glossy, Whatman and Somerset papers exhibited irregular fading rates on exposure to light. The cyan ink from the Epson Photo Stylus printer also produced erratic fading curves. Further testing showed that the inks printed on the Epson coated ink jet papers were photochromatic.
Effect of UV Filter	Use of an UV filter improved light fastness by approximately 35 % for the samples printed on uncoated paper. For the coated papers tested, light fastness was improved by 48 % – 51 %. The Epson Photo Stylus 870 samples showed hardly any visible fading for any of the four primary printing inks after exposure to natural daylight with the UV filter.
Effect of Dichroic Filters	The cyan and yellow inks from the Epson Pro 9000 ink set printed on both the coated and uncoated papers nearly all exhibited erratic fading rate on exposure to the dichroic filters.
Conservation Treatments	All inks were fugitive with the aqueous treatments. The Epson Pro 9000 ink set printed on the uncoated papers were very fugitive to all of the wet treatments and were also sensitive to the moisture from the wheat starch paste used for tear repairs.
Identification	Uniformly sized droplet could be observed on the areas printed at low ink concentrations (25 % and 50 %), under magnification (X 10).
Thermal/Dark Ageing of Coated Papers	All of the Epson coated papers yellowed after thermal/dark ageing. The yellowing was less pronounced on the uncoated side of the paper. Pro 9000 Photo Glossy and Photo Stylus Glossy papers were acidic and became more acidic after dark ageing. The Pro 9000 Presentation matt paper was slightly alkaline and the pH value fell to around neutral after dark ageing.

Table 6.11 Summary of results for the Hewlett Packard printed samples

Test	*Results*
Light Fastness	Magenta ink the cyan, yellow and black HP black ink possibly pigment, see results. Possible dye suggest, due to light fastness rating. Avecia make HP inks and say they are generally azo dyes.
Estimated exposure until JNF occurs (klux hours).	Sample 4.1 – 2,200.
Effect of Paper Substrate	Only one paper tested.
Catalytic Fading	Slight catalytic fading of the dye mixtures was observed on two of the ink patches: Blue (composed of the magenta and cyan ink) and the yellow ink printed with 50 % Black.
Ink Concentration	The magenta ink patch showed the most rapid fading rate when printed at a 100 % ink concentration. All the other inks showed increased fading when printed at 50 % and 75 % concentrations.
Presence of Erratic Fading Rates	The cyan and yellow inks exhibited erratic fading rates on exposure to the natural daylight tests. Further testing showed that these inks were photochromatic.
Effect of UV Filter	Use of an UV filter improved light fastness by approximately 65 % for the samples tested.
Effect of Dichroic Filters	Not tested.
Conservation Treatments	The black ink was slightly fugitive the all of the aqueous treatments tested, but the other inks appeared to be wet fast. The wheat starch paste used for tear repairs did not adhere the coated paper very well.
Identification	Dithering pattern of the ink droplets could be observed at 75 % ink concentration. Size of the printed droplets appeared relatively uniform.
Thermal/Dark Ageing of Coated Papers	The Hewlett Packard Heavy Weight paper yellowed after thermal/dark ageing. The yellowing was less pronounced on the uncoated side of the paper. The paper became more acidic after dark ageing.

Table 6.12 Summary of results for the Canon printed samples

Test	*Results*
Light Fastness	Overall the samples showed good light fastness compared to the ink jet inks but the yellow toners from all three electrophotographic systems proved to have an appreciably higher sensitivity to light than the other toners.
Estimated lux-hour exposure until JNF occurs (klux hours).	Sample 5.1 – 47,000, Sample 5.2 – 23,000, Sample 5.3 – 9,500, Sample 5.4 – 38,000, Sample 5.5 – 38,000.
Effect of Paper Substrate	The paper was the most sensitive component of the Canon printed samples showing significant yellowing on exposure to the natural daylight and Microscal light ageing tests, which caused a shift in colour balance of the toners printed at lower concentrations (25 % and 50 %), towards the yellow portion of the spectrum. The Canon 1150 printed samples exhibited had better light fastness when printed on the Card compared to when produced on the Ultra White paper.
Catalytic Fading	No catalytic fading of the toner mixture was evident with the light fast tests.
Ink Concentration	The black toner patch from the Canon CLC 900 printer showed the most rapid fading rate when printed at 100 % ink concentration. All the other toners showed most rapid fading rates when printed at 50 % and 75 % concentrations.
Presence of Erratic Fading Rates	No erratic fading curves were observed.
Effect of UV Filter	Use of an UV filter improved light fastness by approximately 23 % - 43 %.
Effect of Dichroic Filters	Not tested.
Conservation Treatments	The printed toner was subject to surface abrasions and marking with mechanical dry cleaning. The black toner from the Canon CLBP 460 PS printer was fugitive to the IMS solvent. All of the toners were found to be wet fast.
Identification	Under magnification, lines could be observed running across the printed patches where more than one coloured toner was printed. The toner lies on top of the paper, coating the surface of the substrate.
Thermal Ageing of Coated Papers	All of the Canon papers tested yellowed significantly after thermal/dark ageing. The papers were slightly acidic and became more acidic after thermal ageing.

[1] The majority of azo dyes do not exhibit photochromism as many of the commercial azo-dyes have predominantly hydrazone structures, or have strongly electron-withdrawing groups to the azo linkage, these features either inhibit photoisomerization or reduce the lifetime of the *cis*-isomer. Gordon *et al.* (1987), p.493

[2] Southwark Council, the local council for the Camberwell district, publish the levels of pollutants measured around the borough. Overall, the air quality in 2000 was over the National Air Quality Strategy (NAQS) for levels of sulphur dioxide, nitrogen dioxide and particles (PM_{10}). Ozone was also relatively high (annual mean is 15 ppb) (Air Quality in London, 2000).

[3] P. 189.

[4] Wilhelm found that a the cyan dye from a small selection of colour photographs exhibited faster fading rates under tungsten illumination compared to exposure to fluorescent illumination. He remarked that this was surprising, but concluded on the whole that the fading of photographs was generally not effected by the spectral distribution of the light source. Wilhelm *et al.* (1994), pp. 81-82.

[5] As the wavelengths of the radiation further increases, the damage increases to a maximum in the green-orange section of the spectrum before decreasing in the red region. Saunders *et al.* (1994), p. 192.

[6] Feller reported that a 10 °C rise in temperature doubled the fading rates of selected pigments. Feller (1964), p. 88 and 95.

[7] During daylight exposures in the UK, the black panel temperature will vary between 0 °C and 70 °C approximately. McLaren (1963), p. 79.

[8] "*Fugitive dyes usually exhibit a greater percentage of total colour change during the first few hours of light exposure than do fast dyes*". Bowman *et al.* (1983), p. 41.

[9] P. 702.

[10] P. 701.

[11] P. 708

[12] Wilhelm *et al.* (1994) also comments that the set of criteria in ANSI/NAPM IT9.9-1996 does not make provision for selecting different limits for cyan, magenta, and yellow dye losses, or for different limits different directions of colour balances change. Pp. 91-92.

[13] "*With most pictorial scenes, fading of the magenta dye is more obvious than the same degree of fading of the cyan dye. People are much more tolerant of the fading of yellow dye than they are of losses of cyan and magenta; likewise, a much greater degree of yellow stain can be accepted than would be the case if the stain were of another colour. Yellow contributes very little to the perception of image detail, contrast, or the sense of light and dark; however, the amount of yellow dye present has a significant effect on the hue and warmth of a photograph and is a critical component of skin-tone reproduction*". Wilhelm et al. (1994), p. 90.

[14] "*Some black colourants are designed by bonding a navy blue to an orange dye*". Jürgens (1999), p. 35.

7.0 CONCLUSIONS

7.1 MAIN FINDINGS

7.1.1 Overview of light fastness results

All five of the ink jet print samples tested exhibited sensitivity to light and to the wet treatments in various ink and paper combinations. A majority of the ink jet printed materials showed to be extremely sensitive to light and would produce one JNF after approximately 150 klux – 300 klux hours on display. The Lysonic ink printed on Whatman watercolour paper showed to be more light stable producing one JNF after 16,000 klux hours on display. The electrophotographic print samples performed much better than the ink jet prints in all of the light and conservation tests investigated. The magenta toner from the CLC 900 laser printer showed the most rapid fading rate from all the electrophotographic samples tested, and will produce one JNF after approximately 9,500 klux hours on display (equivalent to blue wool scale 4-5). This result corresponds to the light fastness values published by Schiller (2000), who found that the magenta ink from the Canon CLC 900 faded at the fastest rate equivalent to blue wool scale 4 (see table 3.2). The Canon papers were also shown to be prone to yellowing on exposure to light and in storage.

7.1.2 The effect of the substrate

The type of paper used in ink jet printing made a considerable difference to the light stability and wet fastness of a print. For the Epson Pro 9000 print samples, the preferred combination was the manufacture's matched coated paper and ink jet ink. Samples using the same ink printed on the uncoated Somerset Velvet, Whatman Watercolour and the ink jet coated ISVE papers, produced by independent manufacturers, dramatically reduced the light and wet fastness of the Epson prints. Research published on the relationship between ink jet ink and media (see 3.2.5), reviews the manufacturer's method of treating the development of ink jet ink and media as a whole system. In this system, elements of both components, such as the pH value, are manipulated so that when they are used together, they produce the best printing results. This method is used to obtain the highest quality print possible and for marketing reasons. However, for the Lyson print samples, the inks showed better light fastness when printed on the uncoated Somerset Velvet and Whatman papers.

7.1.3 The effect of different ink combinations/concentrations

Different combinations of the ink jet ink also made a significant difference to the light fastness, due to the phenomenon termed 'catalytic fading of dye mixtures' (Vanmaele, 1995). This study has shown that a wide variety of ink jet ink combinations are necessary, in order to identify the ink sets photochemical stability. Combinations of the CMY ink with 50 % K ink concentration, result in higher fading rates than the same inks printed individually, or in combination. Ink concentration has also proved to have an effect on light fastness, with a majority of the ink samples having a greater fading rate when printed at 75 % and 50 % intensities. Light fast testing of ink jet samples, therefore, should always included a selection of all the possible ink combinations at various concentrations, in order to have a fuller understanding of the ink sets reaction to light.

7.1.4 Light fastness testing

None of the light fast testing methods employed in this investigation were ideal. This is because the environmental conditions within each test were not completely controllable. The results obtained from the light fastness tests, therefore, did not represent the effect of light alone, but also relative humidity, temperature, and in the case of the daylight and tungsten-halogen tests, possibly gaseous and airborne particulates. The fluorescent light fast tester was the superior method employed in this investigation, because temperature was maintained close to normal room conditions, and the exposure area was closed off to the surrounding environment. Relative humidity within the fluorescent test box, however, underwent a disturbance each week when the box was opened to remove the print samples for colour measurement. The box was also not air tight, despite attempts to make it so, and the air inside the box probably underwent many changes during the test. Future testing, using a fluorescent light source, would benefit from an environmentally controlled room, which would allow better control of the testing environment and access to the samples without affecting the exposure atmosphere.

7.1.5 The effect of the dichroic and UV filters

UV filters should always be employed when exhibiting these print materials, since they have shown to be very beneficial in reducing the fading rate of many of the colourants. Most of the ink jet materials were shown to be most sensitive to the violet and blue regions of visible region, even if only a small amount of these wavelengths were absorbed by the ink. Some of the ink jet samples, however, exhibited higher fading rates when exposed to the yellow/orange regions of the spectrum, when using the dichroic filters and tungsten-halogen light source. The variation in the fading rates of these inks appeared to be related to their spectral absorption characteristics. The light sensitivity of the print materials to the different wavelengths in the visible spectrum, suggest that when quoting the fading rate of ink jet images, it is important to consider the type of light source and not just the amount of lux-hours permissible.

A print containing a majority of cyan and/or blue ink may fade more quickly under 50 lux tungsten illumination, than under fluorescent light of the same lux levels. If a print contains a variety of fugitive inks though, a light source that emits a higher proportion of red light would generally be preferable. Yellow filters placed over the light source, by eliminating the violet and blue wavelengths of visible light, could also reduce the fading rate of an ink jet image (Saunders, 1989). However, this may comprise the viewing conditions. Overall, the two inks that showed extreme light sensitivity, the black ink from the Iris Morgan FA ink set and the magenta ink from the Epson Pro 9000 ink set, exhibited rapid fading rates under all of the wavelength regions tested, which probably explains the sensitivity of these inks.

7.1.6 Explanation of the irregular fading rates

Erratic fading rates of a small selection of the ink jet samples were persistently recorded with nearly all the light fast testing methods employed (fluorescent, tungsten-halogen and natural daylight tests). This was an unexpected occurrence, since these inks are designed to produce proofs for the printing industry, where colour accuracy is highly important. No published data has been found so far that documents this phenomenon with ink jet printing.

This behaviour was attributed to two possible phenomenons, photochromism and/or the disintegration of dye particles. The majority of the erratic fading reactions were found to occur when the ink jet inks were printed on the coated papers instead of on the traditional uncoated papers, when samples were exposed to the full visible spectrum. When the Epson Pro 9000 print samples were exposed to the limited regions of wavelengths transmitted by the dichroic filters, irregular fading curves were clearly observed with the cyan and yellow inks printed on the uncoated Somerset Velvet and Whatman watercolour papers as well as on the coated papers. Similar behaviour was also observed with the cyan, yellow and magenta inks from the Iris Morgan FA ink set, printed on the uncoated papers. These results suggest that the *trans-cis* photochromism reaction is being generated by certain wavelengths of light, and is responsible for the irregular fading rates rather than the disintegration of dye particles. A test for the presence of photochromism was also carried out following the guidelines published by BS 1006 B05 (1990), and many of the samples that produced erratic fading curves were found to be photochromatic. The cause of the irregular fading rates of the samples that were shown not to be photochromatic could be attributed to the breakdown of dye particles present in the ink jet samples, but further testing is necessary to gain a fuller understanding of the photochemical reactions taking place (see 8.0).

7.1.7 Colour gamut of ink sets

The inverse relationship between colour gamut and light fastness of a digital printing ink set did not become apparent in this investigation. Using this method to give an approximate insight into light stability of an ink set, is therefore, inadvisable.

7.1.8 The blue wool standards

On exposure to the light fast testing methods employed, the blue wool standards showed varying rates of fading. Previous research has also found irregularities in the spacing on the scale of the blue wool dyes, with the collapse of the relationship attributed to the absorption characteristics of the dyes, the absence of UV radiation (Saunders *et al.*, 1994, Rawlands, 1963, McLaren, 1956) and differences of the dyeings between batches. The use of the blue wool standards has been questioned in the previous studies, and new pigment standards using ratios of two pigments of low and high fastness, along with titanium dioxide, are currently being tested as a replacement for the blue wool dyes (Smith, 1991). The ΔE_{ab} calculation has also been the subject of criticism in the literature as not being an accurate measurement of colour change. The Society of Dyers and Colourists are currently testing a new formulation that should over come the difficulties to replace the ΔE_{ab} equation.

7.1.9 Identification

Although only a small selection of ink jet prints were used for a study of identification techniques, it became clear that due to the wide variety of inks and media available with digital printing, classification of the exact printing process and ink type could be very difficult, if not impossible. Unfortunately, the identification process is very important for the exhibition of this type of media since, as this research has shown, light stability can vary greatly. The conservator/curator must try to obtain as much information about the type of print, inks and media from the artist, previous owner or printing studio, if at all possible, before considering exhibiting this material. Artists and photographers could also help in this process by documenting this information with the work.

7.1.10 Exhibition recommendations

Most of the ink jet prints tested in this investigation exhibited one JNF after 150 klux – 300 klux hours on display (considering different ink concentrations and combinations). Therefore, these prints are not recommended for permanent display. The type of paper used for printing can have a dramatic effect on the light fastness of the image as well, and museums, galleries and artists need to be aware of the data published on the light fastness of ink jet prints and how it can vary with different substrates. The Epson inks showed significantly better light stability when printed on their matched coated papers, but the Lyson inks exhibited had better light fastness when printed on the uncoated papers.

The sensitive of the ink jet images to light, signify that the lowest illuminance possible should be employed if these prints are to be exhibited. This value is usually given as 50 lux (Thompson, 1986, Boyce, 1987). This low level of illuminance for sensitive materials has been criticised in the literature (Michalski, 1997, Boyce, 1997, Hendricks, 1991) because low levels of illuminance can effect the perception of fine detail, slight tonal variations, dark surfaces, and in particular may not be adequate for older viewers (Cuttle, 1988, Michalski, 1997). Light damages museum objects rather quickly, compared to other factors such as RH. Hendricks (1991) and Wilhelm *et al.* (1994) discuss the case of colour photographs, with which ink jet technology is often compared to. They suggest that colour photographs would benefit from being viewed at conditions of at least 300 lux[1]; and Michalski (1997) recommends at least 150 lux for viewing coloured objects. The conservator must therefore, also consider the aesthetic improvements that a higher illuminance level could give, and that perhaps a higher illumination level for only a very limited period of time may be preferred. Thompson (1986) suggests that prints that need to be well lit should be exposed to light with yellow tinted filters, which may not noticeable when placed over light sources rather then between viewer and object. A time-delay lighting system could also be employed. The conservator/curator should also try to obtain the prior exhibition history of the ink jet prints, as the print may have already undergone significant fading or colour change.

At the beginning of this research, it was suggested that if the image had undergone noticeable fading or damage, another print could be reproduced by a digital print bureau or gallery/museum authorised by the artist. This idea is not practical because the market for digital printers is forever changing and like the computer, printer models are often only available for a few years. There is also the danger of fraudulent use. This idea has been practised with photographic collections, however (Winner, 1997). Another suggestion was that the nature of the production method employed in digital printing enables several copies of the same image to be made with ease. Therefore, the artist or photographer could overcome the problem of displaying these images by supplying more than one copy, so that at least one print can be kept as a standard for reference and the other prints exhibited in rotation. This suggestion is also not practical as the additional copies of prints could be then sold on individually.

If the type of printing process, ink and paper used to produce a print is known, a fading monitor printed in same material as the digital print to be exhibited could be made using different ink concentrations and combinations and exposed to the museum/gallery conditions before a digital print is displayed. This method has been employed by Hendricks (1991), for the exhibition of photographs.

Recently, ink jet prints have also been found to be sensitive to ozone (Farr, 2000, Fraser, 2000). The cyan ink from the Epson Photo Stylus 870 printers has been found to readily oxidise and fade on exposure to ozone in the surrounding atmosphere. Epson have since suggested that mounting the ink jet prints behind glass should prevent this reaction from occurring, and there are 'oxygen scavengers', such as RP SYSTEM™, available that can be placed in the frame that remove all oxygen, moisture and pollutant gases from an air tight package.

7.1.11 Thermal ageing

All of the papers exhibited some degree of yellowing after thermal ageing, including the traditional uncoated Somerset Velvet and Whatman papers. The Canon electrophotographic papers showed the most yellowing compared to the other papers tested.

The coating layer on the ink jet coated papers discoloured further that the uncoated fibre based verso. Discolouration of the coating layer is attributed to the presence of fluorescent agents and latex in the surface formulations. The tendency for these papers to yellow, suggests that these prints would benefit from refrigerated storage, to slow down the discolouration process.

Some of the ink jet coated papers were found to be acidic and became more acidic after thermal ageing. Literature published on the composition of ink jet inks and papers discuss the use of differential solubility where the pH value of the papers and inks is manipulated to improve the drying and wet fastness of the produced print (see 3.2.5).

All of the electrophotographic print samples exhibited a possible tendency for the toners to adhere to the covering page if stored in a stack of papers.

7.1.12 Conservation

Overall, results from the conservation tests show that all of the treatments that involve moisture of some kind are generally unsuitable for ink jet printed images. Even tear repairs should be carried out with extreme caution due to the high water solubility of these printing types.

7.1.13 Summary of findings

- Dye-based ink jet prints are very sensitive to light and should not be put on permanent display, with a majority of the prints exhibiting one JNF after 150 klux – 300 klux hours (1-2 years at 50 lux for eight hours per day). The samples produced with the Lysonic ink on Whatman paper showed the greatest light fastness compared to the other ink jet samples and will exhibit a JNF after 16,000 klux hours on display (110 years at 50 lux for eight hours per day). The prints should also not be stored in high humidity conditions, and the exhibition and storage environment must be free from air-borne gaseous particulates and pollutants, which can catalyse the fading reactions.

- The Canon electrophotographic prints exhibited moderately to good light fastness. The CLC 900 laser printer showed the most rapid fading rate from all of the electrophotographic samples tested, and will produce one JNF after approximately 9,500 klux hours on display (65 years at 50 lux for eight hours per day). The samples produced with the Canon 1150 laser printer on Ultra White paper showed the greatest light fastness and will exhibit a JNF after 47,000 klux hours (325 years at 50 lux for eight hours per day).

- Light fastness results published by Wilhelm should be considered with caution, as the criteria employed to calculate the recommended lux hours are not to the same high standards required by museums and galleries, and exposure limits vary considerably.

- The type of paper employed for ink jet prints can make a considerable difference to the light stability and wet fastness of an image. Generally, if the print is produced with an Iris printer, (see Gillet *et al.*, 2000, Wilhelm, 1999) or with Lyson inks, the light stability of the inks is improved when printed on some uncoated papers. If the print is produced on an Epson Pro 9000 printer, the Epson inks will have better light fastness when printed on their matched coated papers than when produced on uncoated papers an ink jet coated substrates produced by other manufacturers.

- The ink jet samples tested with the dichroic filters (the Epson Pro 9000 and Iris sample sets) generally showed to be more light sensitive to the shorter wavelengths of the violet and blue regions of the visible spectrum. Therefore, these prints would benefits from yellow UV filters over the light source, when displayed. This relationship was not evident with the cyan and blue printed samples, which showed that their light sensitivity was determined by the spectral absorption characteristics of the printed patch, and showed more rapid fading rates when exposed to the yellow and orange dichroic filters.

- The museum or gallery should obtain as much information on the make of printer, inks and papers, the date the print was produced and prior exhibition history, before considering exhibiting such work.

- All of the ink jet coated and electrophotographic papers tested were shown to yellow after thermal ageing, therefore, these papers would benefit from storage at low temperatures.

- The toner from the electrophotographic printed materials was shown to possibly migrate and adhere to other papers when stacked in a pile. Therefore, storage of these papers should be considered carefully.

- Future light testing of ink jet prints should include a wide variety of different ink combinations and ink concentrations, to obtain a fuller understanding of the inks sensitivity to light.

- Wet treatments are not advised for the conservation of ink jet and electrophotographic printed materials. Some of the ink jet inks were very sensitive to moisture, and were fugitive when in contact with wheat starch repair paste.

7.2 LIMITATIONS OF METHODOLOGY

7.2.1 Production of printed materials for testing

The sample population investigated in this study was very restricted. Only one sample from each ink jet and electrophotographic set was employed with every test method. A limited number of samples were used because a wide range of ink patches and papers needed to be tested. More than one of each sample would have required at least double the amount of time to perform the research, which was not possible. The limited population infers that the results do not consider the differences in fading that can occur with between samples.

The relationship of the fading rate of the inks printed, as an image, were not examined. Initially, when the print sample layouts were being developed it was thought necessary to only test the fading rate of the ink patches individually. All of the inks however, showed unequal fading losses of either the cyan, magenta, yellow or black inks which can result in a change in colour balance of an image. Therefore, future testing should include an image containing a recognisable subject where the relationship of the light sensitivity of the inks can be recorded against one another. If the inks fade at approximately the same rate, fading is much less noticeable than if the inks faded at different rates[2].

A larger range of printing ink concentrations was needed to obtain a fuller understanding of the relationship between ink intensity and light fastness. A previous investigation into the light stability of Iris ink jet printing, using 10 % printed steps (Allred *et al.*, 1994) inferred a relationship between the light fastness of the ink set and ink concentration. This method may have helped to obtain a better understand of the relationship between ink concentration and light fastness in this investigation. Testing using different dilutions of ink would also aid in establishing a relationship between concentration and light fastness.

7.2.2 Light fast testing environment

The testing environment of the light fastness apparatus employed could not be monitored or controlled to the specifications required. The results collected from the tests, therefore, do not only show how light affects the printed materials, but also may be affected by the following factors: fluctuating humidity; temperature variations; air-borne gaseous particulates and pollutants. Testing, ideally, should be conducted in an environmentally controlled and air-filtered room that allows easy access to the samples without significant disturbance and permits the continuous monitoring and regulation of humidity and temperature. Previous investigations using fluorescent light fastness testing (see table 4.2) also employ a ventilation system, to maintain oxygen levels in the tester.

Effective humidity (E. H.) was also not measured in any of the tests. E.H. is the term given to the relative humidity of the air in contact with the surface of the specimen. This is lower than the overall relative humidity of the testing environment because the surface temperature of the specimen is increased by the absorption of radiation (McLaren, 1963).

The Microscal Light Fastness Tester produced uneven illuminance levels around its perimeter. Therefore, the ΔE_{ab} results calculated from the tests undertaken in this device could be subject to non-uniform exposures. The samples that showed only slight catalytic fading of the dye mixtures could perform another way under different light exposures.

Accelerated light ageing tests cannot guarantee accurate results, even if the reciprocity principle is followed, and environmental conditions are controlled. The most reliable light testing method available is to monitor the fading rate of an object in normal exhibition conditions. Testing, using a very low illuminance level, such as a 1,000 lux employed in the tungsten-halogen test, for a much longer period of time could also produce more reliable results, if other environmental conditions are controlled.

Previous literature has criticised the use of illumination measurement since it does not fully describe the full irradiance of radiation incident on an object, and that as a measurement, it is "*a rather vague unit*"[3]. The lux measurement only measures the amount of light incident on a surface as perceived by the human eye. The illuminance measurement is weighted to the yellow/green region of the visible spectrum, and less emphasis is placed on the violet/blue and orange/red regions of the visible spectrum. Therefore, the illuminance does not measure the irradiance emitted by a light source.

7.2.3 Colour measurement

The frequency at which colour measurements were taken during light fastness testing could have been increased, as the smaller the time interval between measurements the greater the precision. (Saunders, 1989, Bulloch *et al.*, 1999). The colour measurement device used (Minolta CR300 Chroma Meter) recorded an average of three readings for every sample measurement recorded. The number of measurements taken could be increased to, for example, 3 (average of nine measurements) or 5 (average of 15 measurements), for better accuracy.

The accuracy of the colour measurement calculation ΔE_{ab} has already been discussed in 4.3.6. According to published research by Gilchrist *et al.* (1999), the ΔE_{ab} calculation will disagree with the majority of visual decisions about 19 % of the time. A new equation is currently being tested by the Society of Dyers and Colourists that should improve the accuracy of the calculation and will be introduced later this year.

Only one viewer was available to record the visual difference of the blue wool scales and printed samples exposed to the light fast testers. Feller (1978) recommends that the blue wool cloths should be rated by two to three observers, for better accuracy.

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[1] Hendricks (1991) suggests 300 lux is a good compromise between requirements to satisfactorily viewing a photographic print and the need for preservation.

[2] "*Unequal losses of cyan, magenta, or yellow dyes that result in changes in colour balance are much more noticeable than density losses when all three dyes have faded approximately the same amount.*" Wilhelm *et al.*, (1994), p. 91.

[3] Padfield (1996), p. 2.

8.0 DEVELOPMENT OF RESEARCH

The literature published by Wilhelm Imaging Research Inc., and the digital printing manufacturers, on the light fast standards of ink jet printed materials, they should always be considered with caution, as their testing specifications are set to a lower criteria than the needs of conservation. Future testing should include samples of all the different types of ink jet and electrophotographic printed materials used by artists and photographers, in order to create a database of light fastness results. It would also be important to test the effect of a greater variety of substrates, such as the coated canvases and textiles developed for ink jet printing, and to try and identify the most stable ink and paper combinations. Further studies could also be made into the composition of the inks and paper that produce the better light fast results, in order to establish why they give the best results.

Using larger print samples with the aqueous conservation tests would enable a better assessment of how the paper would react with washing treatments. Previous research has found that electrophotographic print materials can wet unevenly during washing treatments, causing distortions in the substrate (Norville-Day, 1994). This result was not observed in this investigation, but the samples tested were relatively small.

A greater range of ink concentrations should be used with any future light fast testing investigation as specified in 7.2.1. Different concentrations of dye in the inks could also be tested to investigate where this has an effect on the light fastness. An image composed from the ink sets tested should also be exposed alongside the print samples to establish how the fading rates of the ink set effects the other printed colours. Future testing would benefit from better environmental control. Exposures close to normal room conditions found in a museum or gallery should also be included, in order to provide a more accurate long-term assessment.

The ANSI have suggested for daylight light fast testing fluorescent daylight tubes could be used instead of natural daylight. Fluorescent tubes are proposed so that the test has better repeatability than is possible with the tests using natural daylight. The required wavelength distribution of the lamps is detailed in the standard and intensity of 6.0 klux is specified for indoor daylight tests. Further light testing could also include exposure to thermal/dark ageing methods after light ageing to evaluate the degradation of the samples combined with the effect of light. Light fast testing research using a 10 °C temperature rise with light fading tests is currently in progress at the National Gallery, London, to establish whether these conditions could give a better representation of the ageing of paper-based material on display[1].

An investigation into the samples that produced the irregular fading rates when exposed under the dichroic filters should also be conducted. One probable cause of this occurrence was attributed to the phenomenon of photochromism, which was identified to take place on some of the samples in a previous study. Future testing should expose the selection of print samples under the various dichroic filters following the method discussed in BS 1006 B05 (1990) to test for the presence of photochromism. A spectrophotometer could also be employed to measure the samples immediately after they are taken out of the light test, to see if the instrument can detect the bathochromic shift, which is acknowledge to occur with the phenomenon.

If photochromism was found to be the cause of the irregular fading rates, further testing would then need to be conducted to assess which wavelengths were instigating these reactions.

The disintegration of the dye particles in the inks was also considered as a possible explanation for the erratic fading rates. Further testing of the particular inks should be performed to confirm this reaction using soap-boiling. This method for testing the effect of aggregates on light fading of a dye uses regenerated cellulose films (cellophane) dyed with the particular ink, one sample is left plain, the other is soap-boiled. The soap-boiling is sufficient to cause the growth of particles in the film which can be visible under a microscope. The samples are then exposed to a light fast tester and the fading rate is recorded as normal.

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[1] Private correspondance with David Saunders, conservation scientist, National Gallery, London.

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APPENDIX A – Glossary

Absorption – the sucking up or assimilation of one substance by another, such as inks or moisture by paper, or the taking up of energy from light.

Acidic – below pH 7.0.

Acuity – sharpness

Ageing – a general term describing the natural degradation of paper, adhesives and other archival materials, while in storage.

Aggregate – to cluster in a dense mass.

Airborne pollutants – substances present in the air that pollute the environment.

Alkaline – above pH 7.0.

Alumina – aluminium dioxide (AlO_2)

Anion – a negatively charged ion.

Apparent resolution – resolution of a print as it appears to the naked eye.

Archival – a general term used to describe objects that do not show signs of ageing after long term storage (long term is defined as 100 years for archival documents).

Banding – horizontal, parallel lines in an ink jet print caused by a falsely aligned or blocked print head.

Bleed – see wicking.

Blue wool scale – consists of eight pieces of blue dyed wool cloth, with the fading rate of each cloth half that of the previous cloth in the scale. Therefore, blue wool scale one fades in half the time of blue wool scale two, and blue wool scale two fades in half the time of blue wool scale three, and so on.

Brightness – a measure of the lightness/whiteness, particularly referring to paper.

Bubble jet printer – see thermal ink jet printer.

Cation – a positively charged ion.

Cellulose – a complex carbohydrate constituting the chief part of the cell walls of plants, yielding many fiborous products, and being commonly obtained from vegetable matter (as wood or cotton) as a white fiborous substance used on large scale for papermaking.

Charge Controlling Agents (CCAs) – used in electrophotographic toner, the CCA is employed to pass on and control an electrostatic charge needed to direct the toner particles to the image areas on the photoconductive drum.

Charge Generating Layer (CGL) – used in electrophotographic systems, the CGL is composed of molecules which, when exposed to light, separate into an ion-pair complex that produce electrical charges proportional to the amount of incident light. CGLs tend to be made from coloured pigments, and often absorb light between 400 nm to 700 nm (visible light).

Charge Transporting Layer (GTL) – used in electrophotographic systems, the GTL is composed of an electron-rich compound which transports a positive charge through the transporting layer to form a positive hole that then combines with a negative electron at the surface of the GTL, creating a neutralised area. This neutralised area thus forms the latent image, used to attract toner for printing.

Chroma meter – a device for measuring the colour of a given object in terms of it spectral reflectance

Chromatography – (chemistry) a method of chemical analysis of a liquid mixture by passing the mixture along an absorbent material such as paper or chalk, the parts of the mixture separating into different layers as they seep along.

Chromophore – a specific arrangement of atoms leading to absorption of photons at specific wavelengths within the spectrum of a light source

CIELAB – three-dimensional colour space model with the parameters L*: measure lightness, a*: measures colour range red to green, b*: measure the colour range blue to yellow.

Coating – term applied to the layer of adhesive mixture of a clay or mixture of pigments, applied to the surface of paper to provide a smooth base for printing.

Cockling – describes when a sheet of paper becomes uneven/wavy surface due to the absorption of moisture.

Colorimeter – see chroma meter

CMC (l : c) ($\Delta E_{CMC(l:c)}$) – type of colour difference equation using the CIELCH coordinates.

Colorant – a substance, usually a dye or pigment, with the ability to absorb and reflect a certain range of wavelengths of visible light. The reflected wavelengths perceived as colour.

Conservation – preservation of objects using interventional methods.

Continuous ink jet – an ink jet system that employs a continuous stream of ink droplets ejected from a print head. Each droplet can be given an electrical charge so that the stream of droplets can be manipulated to form an image.

Continuous tone (contone) – a printing process capable of producing a gradual and virtually smooth scale of tonal changes.

Co-polymer – a combination or two or more different types of polymer in one molecule.

Cotton rag paper – paper made from cotton fibres rather than, or in addition to, tree fibres.

De-acidification – The addition of alkaline compounds to acidic paper to neutralise paper.

Degradation – refers to the chemical decomposition of materials.

Delta E (ΔE_{ab}) – a type of colour difference formula, which uses CIELAB coordinates.

Delta E*$_{94}$ (ΔE^*_{94}) – a type of colour difference formula, which uses CIELAB coordinates and is slightly more accurate than the ΔE_{ab} equation.

Densitometer – A quality control device, which can measure the actual or apparent density of a transparent film or films of ink.

Density – see optical density.

Dichroic filters – allow for the selective transmission of wavelength regions from the visible spectrum.

Digital – data consisting of or systems employing discreet steps or levels, as opposed to continuously variable analog data.

Disperse – to distribute more or less evenly throughout a medium.

Dithering pattern – random ink jet dot pattern (often visible to the naked eye).

Dissolve – to break up a substance into its component parts by uniformly mixing it into a liquid medium.

Dot gain – refers to when the ink hits the paper and spreads out.

Dots per inch (dpi) – measurement of printer output resolution.

Drop-on-demand (DOD) – an ink jet system which employs pressure pulses generated by a piezo crystal that cause ink to be ejected from a print head only when required.

Dye – a form of colorant consisting of single molecules that dissolves in solvents to form clear, coloured solutions.

Dye sublimation – a non-impact printing process, which involves the sublimation of a solid ink, when heated, directly into a vapour phase without first melting to a liquid state. The inks used are dyes dispersed in a polymeric binder.

Electromagnetic spectrum – composed of a continuous spectrum of different wavelengths ranging from cosmic rays (10^{12}) to radio waves (10^{4}).

Electrophotographic printing– includes laser and photocopying systems, the process is based on forming an electrostatic images by photoconductive discharge of an electronically charged surface.

Electrostatic copier – A printing device that transports an electrostatically charged surface onto a printing paper, which is then used to attract liquid toner that is either rolled or sprayed onto the latent image and fused to the paper by heat. This process produces limited quality prints.

Excited state – the state of a molecule after it absorbs energy.

Feathering – see wicking.

Fluorescent light – composed of a glass tube (generally) with electrical contacts or electrodes mounted at each end. The tube is sealed to contain an excitant gas or vapour that becomes ionised when an electrical charge is applied, releasing a electron which give rise to the emission of photons. Fluorescent lamps produce a line source of radiation.

Gamut – a range of colours that can be produced by a device such as a computer monitor or printer.

Gliclée – a fine art ink jet print.

Grammage (gsm) – the weight of paper expressed in grams per square meter.

Grey scales – the range of tones that can be reproduced by a printer.

Ground state – the state of a molecule before it absorbs energy.

Halftone – the reproduction of a photographic image in which the shades or 'tones' of the original are simulated by patterns of dots of varying sizes.

Humidification – a conservation treatment that increases the amount of moisture in an object such as paper, to relax creases, smooth out an uneven sheet, and/or aid the removal of degradation products, for example.

Hydrogen bonds – a type of bond formed when a hydrogen atom bonded to atom 'X' in one molecule makes an additional bond to molecule 'Y' either in the same or another molecule.

Hygrometer – a device for measuring relative humidity.

Infra-red (IR) radiation – refers to the region of wavelengths from the electromagnetic spectrum ranging from 780nm to 1nm.

Ink – substance (solid or liquid) used for writing or printing, generally composed of a colorant, solvent or vehicle and various additives.

Ink jet printing – a printing process in which the image is formed by tiny droplets of ink that are propelled from a print head directly onto the printing substrate.

Ion – an electrically charged atom or group of atoms.

Inorganic – refers to substances that do not contain carbon atoms (see organic) (chemistry).

Kognation – occurs with thermal ink jet printing, caused by the thermal decomposition of organic matter from the inks, which deposit onto the heating elements of bubble jet print heads, leading to insulation of the element and failure of the print head.

Laminate – the bonding of layers of clear material by means or pressure, heat, adhesives or a combination of these, that is applied to one or both sides of a medium after printing, to protect the image.

Laser – acronym for light amplification by simulated emission of radiation. A highly concentrated, directional light source capable of fine control via computerized pulsing systems.

Laser printing – a printing device in which a laser is used to selectively discharge a charged surface, which is then used to attract toner to form an image.

Light fast – resistant to photochemical degradation.

Lignin – substances in trees that, if not removed from pulp cause paper to deteriorate rapidly.

Line source lamps - radiate light at specific wavelengths.

Lux – a measurement of light, which is visible to the naked eye (illuminance), in lumens per square meter.

Lux meter – a device to measure lux.

Mechanical wood pulp – Groundwood pulp made by grinding trees into fibres without removing lignin.

Mercury-vapour lamp – similar principle to the fluorescent lamp, but instead mercury-vapour is used as the excitant material, to produce a form of light similar to natural daylight. This form of light produces a line source of radiation.

Micron (μm) – micrometer, unit of length equal to 10^{-6} meters.

Mordant – a chemical used to fix a dye in or on a substrate by combining with the dye to form an insoluble compound.

Nanometer (nm) – unit of length equal to 10^{-9} millimetres.
Nozzle – the orifice in the print head from which ink is ejected for printing.

Optical density – refers to the thickness of the ink film; the opacity of photographic film emulsions (also known as print density).

Organic – (chemistry) substances that contain carbon atoms.

Organic Photoconductor (OPC) – used in electrophotographic systems, the OPC is a dual layer device composed of a thin charge generating layer (CGL) coated with a thicker charge transporting layer (CTL). This dual layer is deposited onto an aluminium polyester substrate, which is earthed.

Orifice – see nozzle.

Oxidation – a decomposition process caused by oxygen and/or oxygen radicals.

pH – negative logarithm to base of 10 of the hydrogen ion concentration. The letter pH stand for pouvoir hydrogène or 'hydrogen power'.

Phase change ink jet – an ink jet system in which heat is used to melt coloured wax-based inks. The melted inks are then propelled through a print head nozzle using thermal drop-on-demand technology. The droplets of ink solidify when printed on the surface of the substrate, producing highly saturated coloured images.

Photoconductor – see organic photoconductor.

Photocopier – A device that produces a copy of an original document either by electrostatic techniques or digital imaging.

Photon – a quantum of radiant energy.

Phototenderning – refers to a photochemical mechanism generally associated with very light fast dyes. Very light fast dyes tend not to be significantly sensitive to light of wavelengths longer than 400 nm, but the fibre rather than the dye absorbs light and causes reduction of the dye bound to the fibre, or in some cases, the dye may act to transfer absorbed energy to the fibre. Both the fibre and the dye are decomposed as the result.

Piezo crystal – a crystalline material that expands when small electrical impulses are passed through the material.

Pigment – a colorant consisting of a natural crystalline molecule or an agglomerate of synthetic dye molecules.

Polymer – a compound consisting of giant molecules formed from smaller molecular of repeating structural units (known as monomer units).

Preservation – refers to the process in which environmental factors such as temperature, relative humidity, etc., are controlled to slow down the degradation process of museum/gallery objects.

Printing – any process that repeatedly transfers onto paper or other material an image or text from an original such as a mechanical, negative, digital file, or printing plate.

Proof – A test print used for final colour correction before printing.

Recto – the front side of a substrate.

Reduction – refers to the photochemical mechanism whereby an energy-activated molecule such as a dye, reacts with a neighbouring molecule, such as a fibre, to reduce the dye and oxidise the fibre.

Relative humidity (RH) – the ratio expressed as a percentage, of the amount of water vapour actually present in the air to the greatest amount of vapour the air could hold at that temperature.

Resin – a polymer produced in granules or powder form, generally for use in surface coatings.

Resin coated paper – a term used for photographic paper with most colour and some black and white printing applications. The paper has a polyethylene coating on each side.

Resolution – the process of making up an image from very small and discrete entities such as pixels, or ink dots; a measure of the greatest amount of detail or sharpness that can be printed by a device.

Scanning Electron Microscope (SEM) – refers to a type of microscope that has a large depth of field allowing clear photographic images to be recorded. Magnifying range between X 10 and X 1,000,000.

Show-through – occurs when ink penetrates into a paper substrate and is visible from the back, also known as print through.

Silica – silicon dioxide (SiO_2).

Sizing – a gluey substance such as resin, gelatine or starch used for finishing, modifying, and filling the pores of a paper surface to control the papers resistance to the penetration of water present in water-based inks; and with coated papers, to help coatings adhere to base sheets.

Solvent – a substance (usually a liquid) capable of dissolving or dispersing another substance.

Spectrophotometer – a device which measures reflected or transmitted colour in terms of spectral wavelengths.

Spectrum – see electromagnetic spectrum.

Standard deviation – a statistical calculation to evaluate how results from a group of data deviates from their average value (recorded as a percentage).

Substrate – The base material such as paper, board, film, etc. upon which ink is deposited in the printing process. Substrate is also the carrier for paper coatings.

Surfactant – substances that enable the dispersion or solution of non-polar molecules in polar liquids or vice versa.

Thermal ageing – Ageing using dry heat or combined high temperature and high humidity.

Thermal wax transfer printing – a non-impact printing process that employs a wax coated film that is brought into contact with the printing paper, and the colorant is transferred by action of a thermal head that is controlled by a digital signal.

Thermal ink jet printing – a type of drop-on-demand ink jet system, which employs heat to repulse a droplet of ink from a print head when required.

Toner – used as the colorant in electrophotographic systems, toner is composed of pigments dispersed in thermoplastic resins and charge controlling agents (CCAs).

Tungsten-halogen light - a filament of tungsten is heated by an electrical current to a temperature at which it emits light as well as heat. When heated, tungsten evaporates from the lamp filament and in the presence of halogen gas, it reacts to form a gaseous tungsten halide, which then migrates back to the hot filament, where it decomposes, depositing some tungsten back to the filament and releasing halogen back into the bulb atmosphere. This process enables the light source to last longer than ordinary tungsten lamps.

Ultra violet (UV) radiation – refers to the region of wavelengths from the electromagnetic spectrum ranging from 400 nm to less than 280 nm. In daylight, UV radiation is present from 300 nm to 400 nm.

Vehicle –a term given to a fluid that serves as a carrier for dissolved or dispersed dyes or pigments in order to give them mobility needed to transport the colorants through the printing device and onto the substrate.

Verso – the reverse side of a substrate.

Viscosity – the tendency for a liquid to flow slowly or quickly resulting from the friction of its molecules.

Wet fastness – resistance to the solubility of water.

Wicking – to draw moisture by capillary action; in the context of ink jet printing, the term refers to when the ink spreads along paper fibres resulting in loss of edge acuity and overall print quality.

APPENDIX B - List of computer printers employed by artists and photographers

The following list was compiled from reviewing published literature, correspondence during the research and from discussions with the research project *The Integration of Computers within Fine Art Practise*, based at Camberwell College of Arts, London. This research project has been established since 1994 and has involved work from the artists Paul Coldwell, Charlotte Hodes, Barbara Rauch, Tim O'Riley, Tristan Humphries, Naren Barfield, Jeffrey Edwards, Grenville Davey, Kathy Prendergast, Stella Whalley, Cian Quale, Peter Lee and George Whale.

B.1 INK JET PRINTERS

B.1.1 Epson Printers

Artist	*Printer*	*Printing paper*	*Ink*
Andrew Atkinson (correspondence)	Epson Stylus 1520	Canon HR-101 High resolution paper	Not listed
The Integration of Computers Within Fine Art Practice	Epson Pro 9000	Epson Presentation Matt, Whatman, Somerset, Epson transparent film	Epson Pro 9000 inks
The Integration of Computers Within Fine Art Practice	Epson Pro 9500	Epson Presentation Matt, Whatman, Somerset, Epson transparent film	Epson Pro 9500 inks (pigment)

B.1.2 Hewlett Packard (HP) Printers

Artist	*Printer*	*Printing paper*	*Ink*
The Integration of Computers Within Fine Art Practice	HP 3500HP	Heavy Weight Matt	HP 3500 inks
Henry Reichold (correspondence)	HP 3500	HP Photo Glossy HP Canvas	HP 3500 inks

B.1.3 Iris Printers

Artist	*Printer*	*Printing paper*	*Ink*
Chuck Close (Miller, 1998b)	Iris 3047	Not listed	Not listed
Jim Dine (Miller, 1998b)	Iris 3047	Not listed	Not listed
Maxine Hall (correspondence)	Iris 3047	Arches Watercolour	Not listed
Richard Hamilton (Hamilton, 1998)	Iris 3047	Somerset paper	Morgan FA, Lysonic
Paula Moss (correspondence)	Iris 3047	Arches Watercolour	Not listed
Robert Rauchenberg (Simpson, 1998)	Iris 3047	Not listed	Not listed

B.2 ELECTROPHOTOGRAPHIC PRINTERS

Artist	*Printer*	*Media*	*Toner*
David Hockney (Norville-Day, 1994, Norville-Day *et al.*, 1998, Lightfoot, 1995)	Canon PC-25, Canon NP-3525 Kodak EK 225-F	Arches Text 100 % cotton rag, 120 gsm	Not listed
Mark Tansey (Lightfoot, 1995)	Not listed	Not listed	Not listed
Carl Tooth (Lightfoot, 1995)	Not listed	Not listed.	Not listed
Ray Johnstone (Lightfoot, 1995)	Not listed	Not listed.	Not listed
Tulla Lightfoot (Lightfoot, 1995)	Not listed	Not listed	Not listed

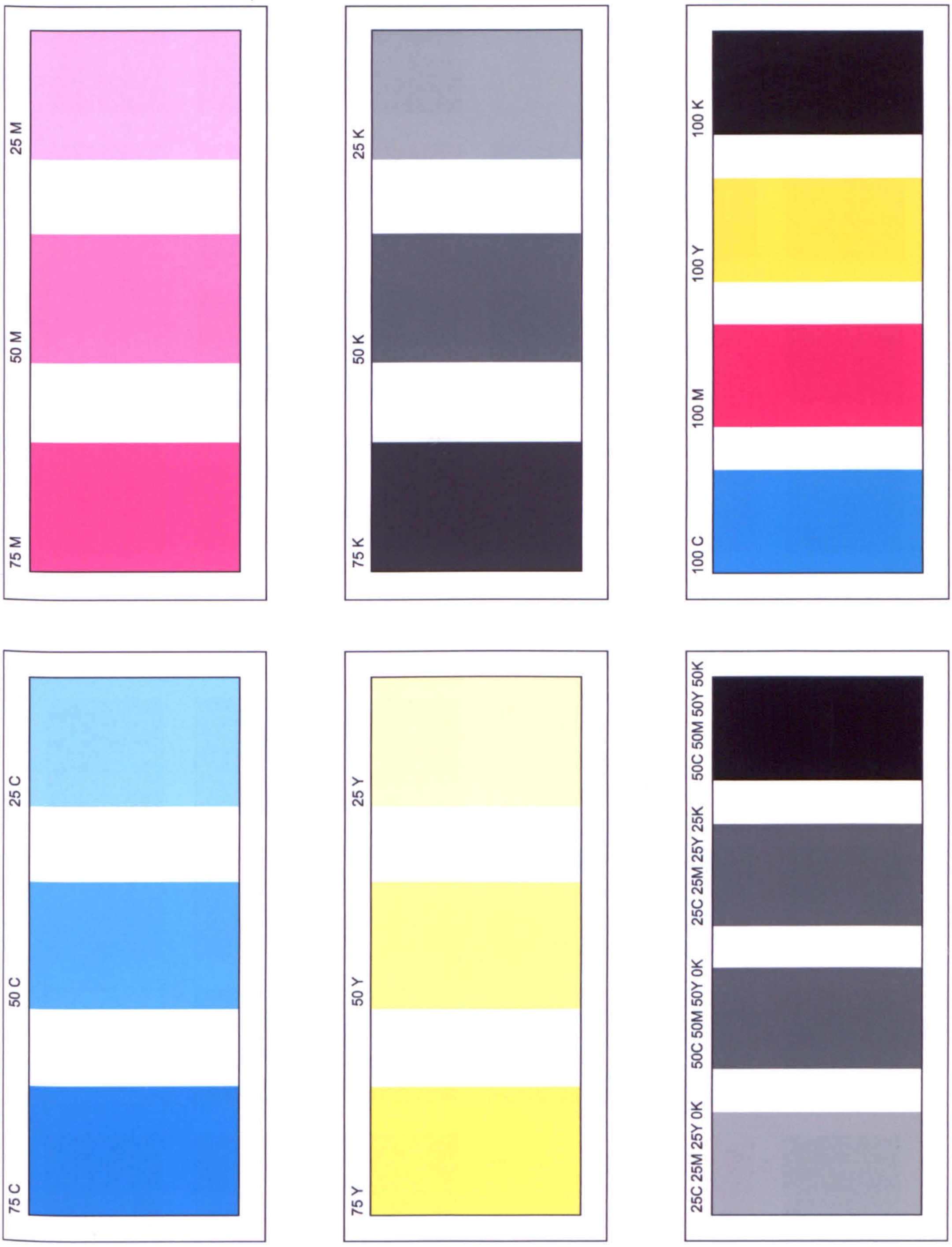
B.3 OTHER DIGITAL PRINTING PROCESSES

Artist	*Printer*	*Media*	*Inks*
The Integration of Computers within Fine Art Practice	Encad Novajet III (ink jet printer)	Whatman watercolour, various coated Papers	Vectojet refill inks
Tony Lee (The Intergration of Computers within Fine Art Practice)	Tektronix (phase change ink jet)	Not listed	Tektronix Phase change inks
Diane Longley (Speck, 1998)	Encad Novajet (ink jet printer)	Not listed	Not listed
Olga Sankey (Speck, 1998)	Encad Novajet (ink jet printer)	Not listed	Not listed
Bibo Viro (correspondence)	Lambda 130 (digital Photographic process)	Cibachrome paper	Not listed.
	Colorspan (uses an Iris ink jet print engine)	Iris Canvas, Arches Cold Press	Indura-chrome

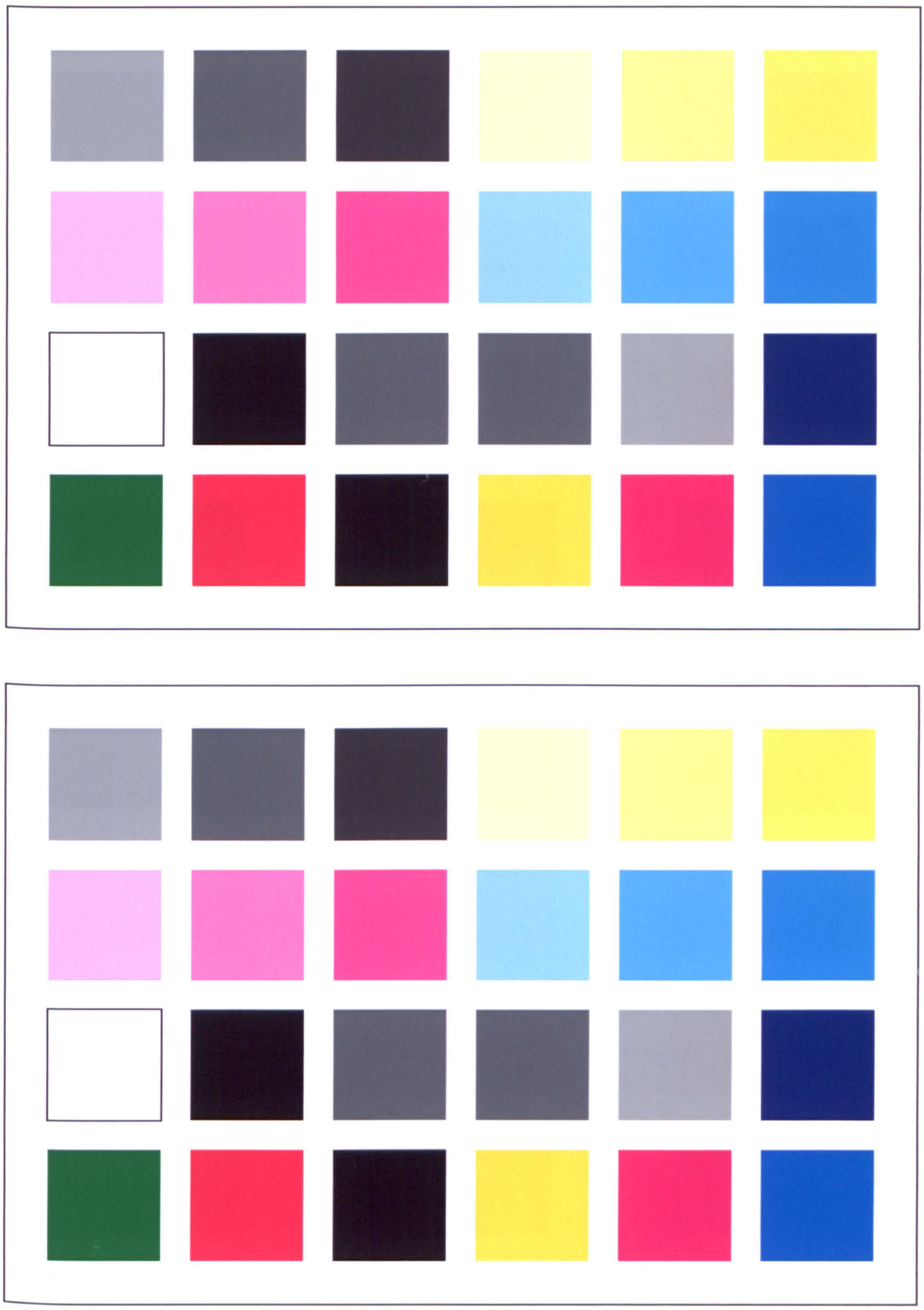
APPENDIX C - Print layouts

C.1 Image quality print layout

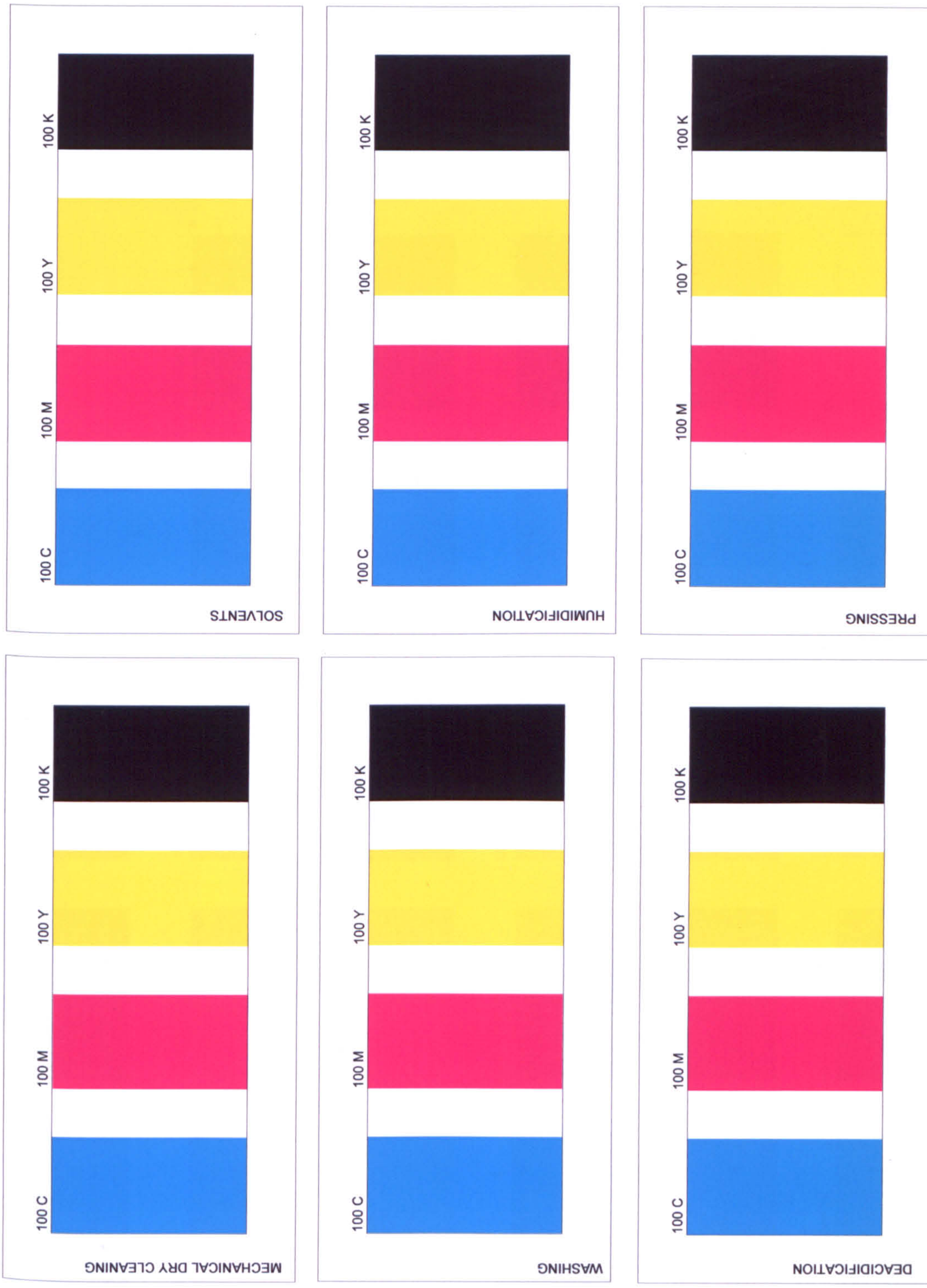
C.2 Light fastness print layout no. 1.



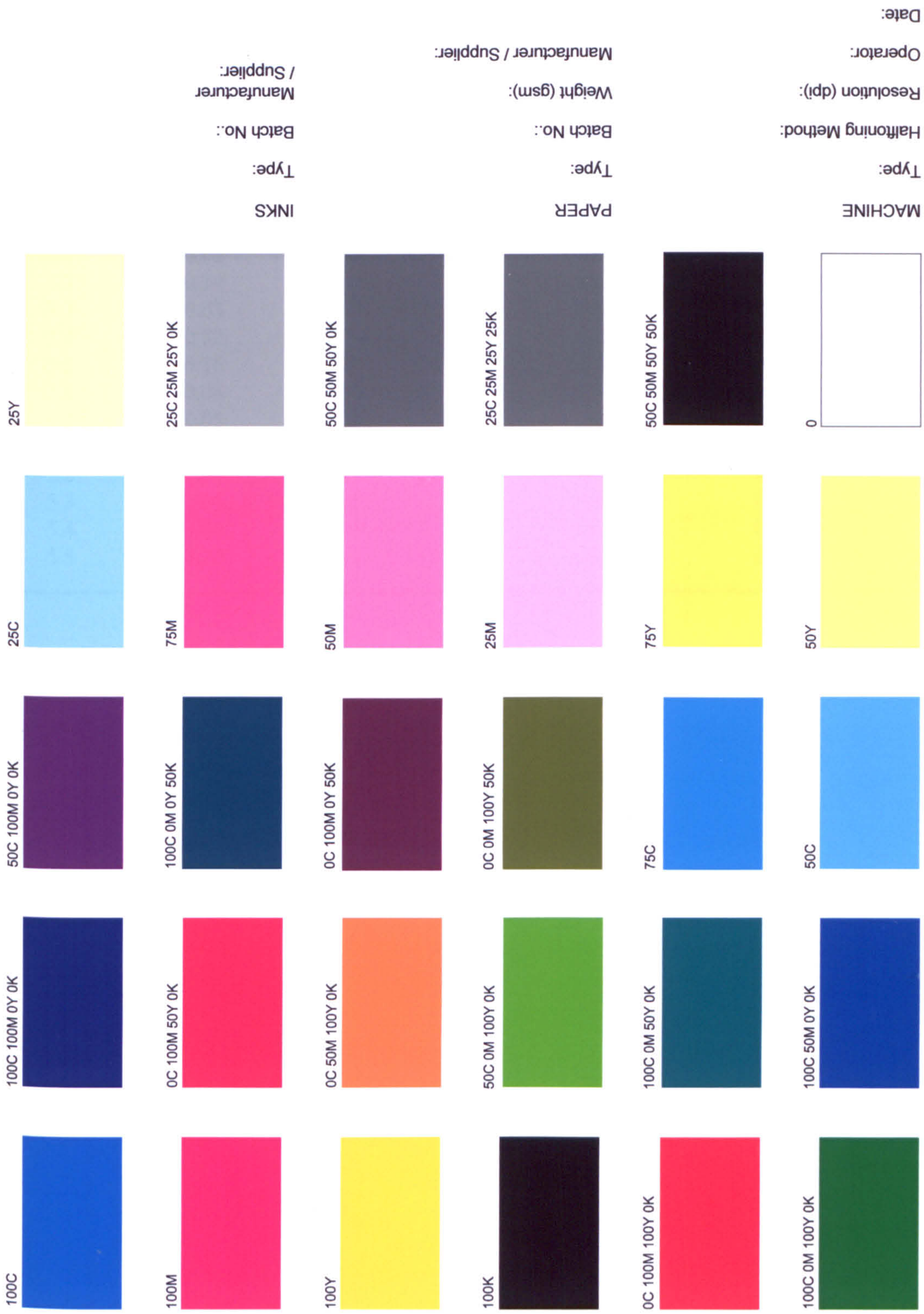
C.3 Light fastness print layout no. 2.



C.4 Fluorescent light fastness print layout no. 3.



C.5 Conservation print layout.



C.6 Control print layout.

APPENDIX D - Standard deviation results

Sample no.	*Cyan*	*Magenta*	*Yellow*	*Black*	*Average SD for ink set*
1.1	0.15	0.07	0.06	0.08	0.09
1.2	0.08	0.02	0.04	0.04	0.05
2.1	0.07	0.09	0.09	0.09	0.02
2.2	0.11	0.07	0.17	0.14	0.03
2.3	0.09	0.03	0.09	0.08	0.02
2.4	0.17	0.05	0.04	0.04	0.01
3.1	0.08	0.07	0.1	0.07	0.08
3.2	0.14	0.31	0.19	0.11	0.19
3.3	0.03	0.05	0.19	0.03	0.07
3.4	0.82	1.03	1.93	0.67	1.11
3.5	0.16	0.22	0.24	0.21	0.05
3.6	0.08	0.06	0.08	0.09	0.08
4.1	0.05	0.04	0.14	0.1	0.03
5.1	0.09	0.08	0.06	0.17	0.04
5.2	0.04	0.07	0.22	0.04	0.01
5.3	0.06	0.05	0.10	0.02	0.01
5.4	0.09	0.14	0.13	0.04	0.01
5.5	0.20	0.10	0.15	0.07	0.02

APPENDIX E - Equipment manufactures and suppliers

Colour measurement manufacturers

Minolta (UK) Ltd., Rooksley Park, Precedent Drive, Rooksley, Milton Keynes MK13 8HF.

Xrite (UK) Ltd., The Acumen Centre, First Avenue, Poyton, Chesihire SK12 1FJ.

Computer software

Adobe, website address: www.adobe.com.

Conservation equipment and supplies

Bondina Industrial Ltd., Greetland, Halifax, Yorkshire HX4 8NJ.

Conservation Resources UK Ltd., Units 1, 2, 4, Pony Road, Horsepath Industrial Estate, Cowley, Oxford OX4 2RD

Preservation Equipment Ltd., Vinces Road, Diss, Norfolk, IP22 4HQ

RP SYSTEM™ scavengers supplied by Conservation By Design, Timecare Works, 5 Singer Way, Kempston, Bedford MK42 7AW.

UV filter manufactures

Film Technologies International Inc. supplied by The Bonwyke Group, Bonwyke House, 41, Redlands Lane, Fareham, Hampshire PO14 1HL

Dichroic filter manufacturers

Unaxis Balzers Limited, Division Optics, PO Box 135, North West, Manchester M28 0PE.

Ink jet and electrophotographic manufacturers (printers and consumables)

Canon (UK) Ltd., The Harlequin Centre, Southall Lane, Southall, Middlesex UB25NH.

Epson (UK) Ltd., Campus 100, Maylands Avenue, Hemel Hempstead, Herts. HP2 7TJ.

Hewlett-Packard (UK) Ltd., Cain Road, Bracknell, Berkshire RG12 1HN.

Lyson Ltd., 7 Barton Road, Heaton Mersey Industrial Estate, Heaton Mersey, Stockport SK4 3EG.

Laboratory and environmental monitoring equipment and supplies

Merck BDH, supplied by R&L Slaughter Ltd., Units 11 & 12, Upminster Trading Park, Watley Street, Upminster, Essex RM14 3PJ.

Light fast testing equipment and suppliers

Dexion Frames, supplied by Duval Products Ltd., Armoury Way, Wandsworth, London SW18 1EU.

Microscal Ltd., 79 Southern row, London W10 5AL.

Osram Ltd., PO Box 17, East Lane, Wembley, Middlesex HA9 7PG.

Phillips Lighting UK, The Philips Centre, 420-430 London road, Croydon Surrey CR9 3QR.

Specialist Lamp Distributors, 30 Factory Lane, Croydon, CRO 3RL.

Paper manufactures

Inveresk, St. Cuthberts Mill, Wells, Somerset BA5 1AG.

Whatman International Ltd., Whatman House, St. Leanard's Road, 20/20 Maidstone, Kent ME16 0LS.

Print bureaux

Visualeyes Ltd., 24 West Street, Covent Garden, London WC2H 9NA

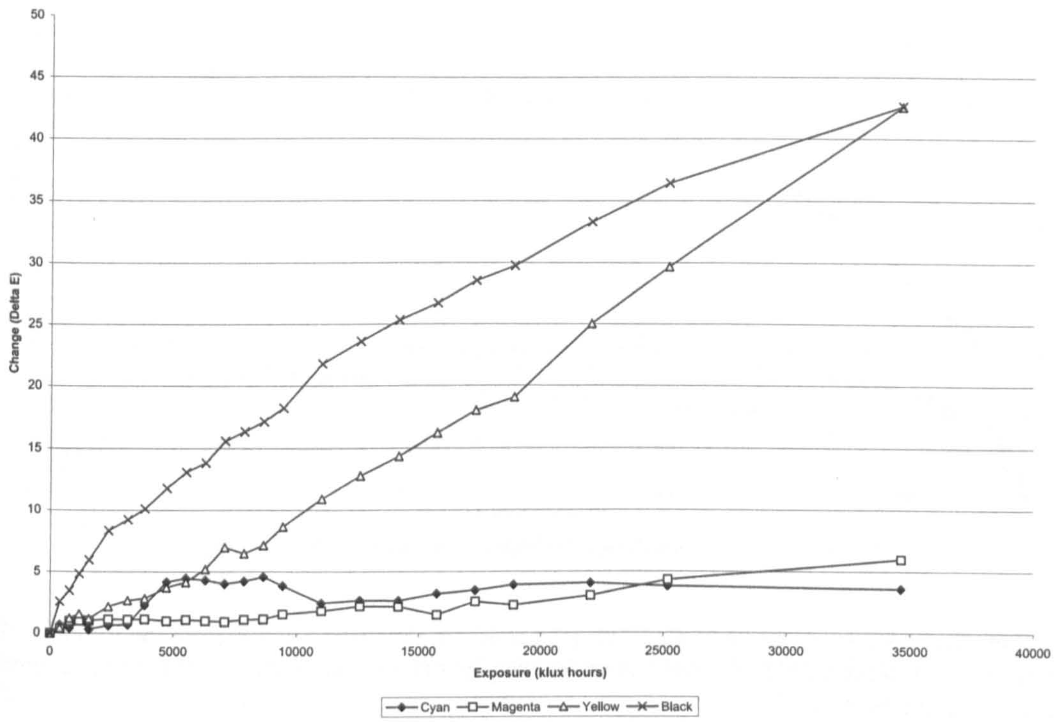
Scanning Electron Microscope

JEOL (UK) Ltd., JEOL House, Silver Court, Watchmead, Welwyn Garden City, Herts. AL7 1LT.

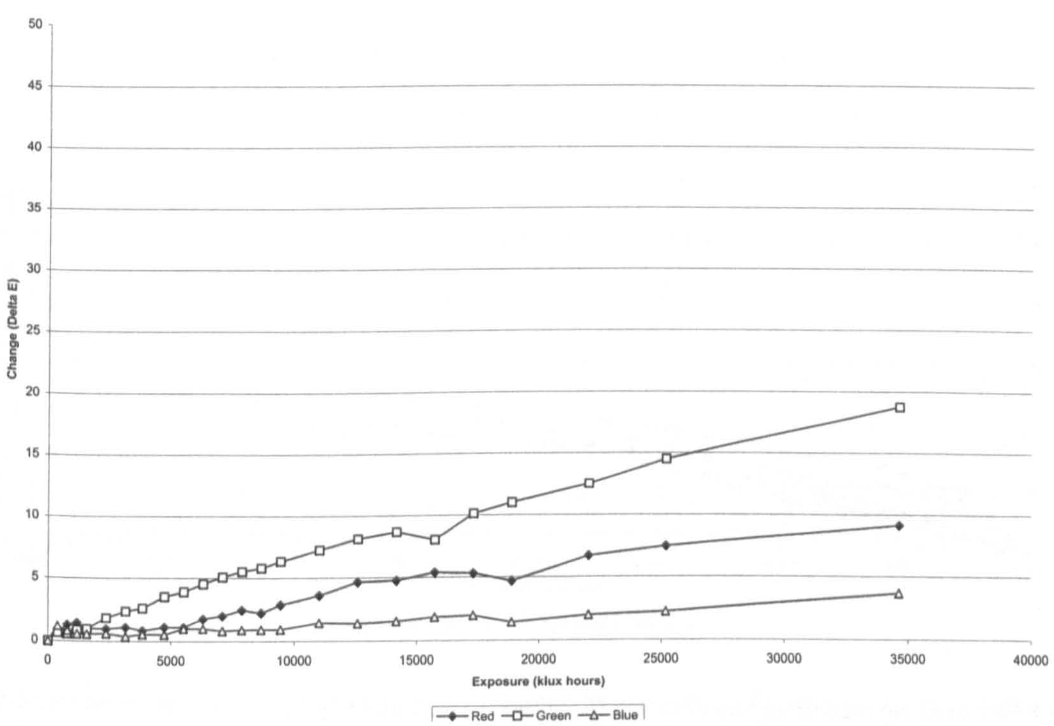
Thermal ageing equipment

Gallenkamp, 50 Bishop Meadow Road, Loughborough, Leics. LE11 ORE

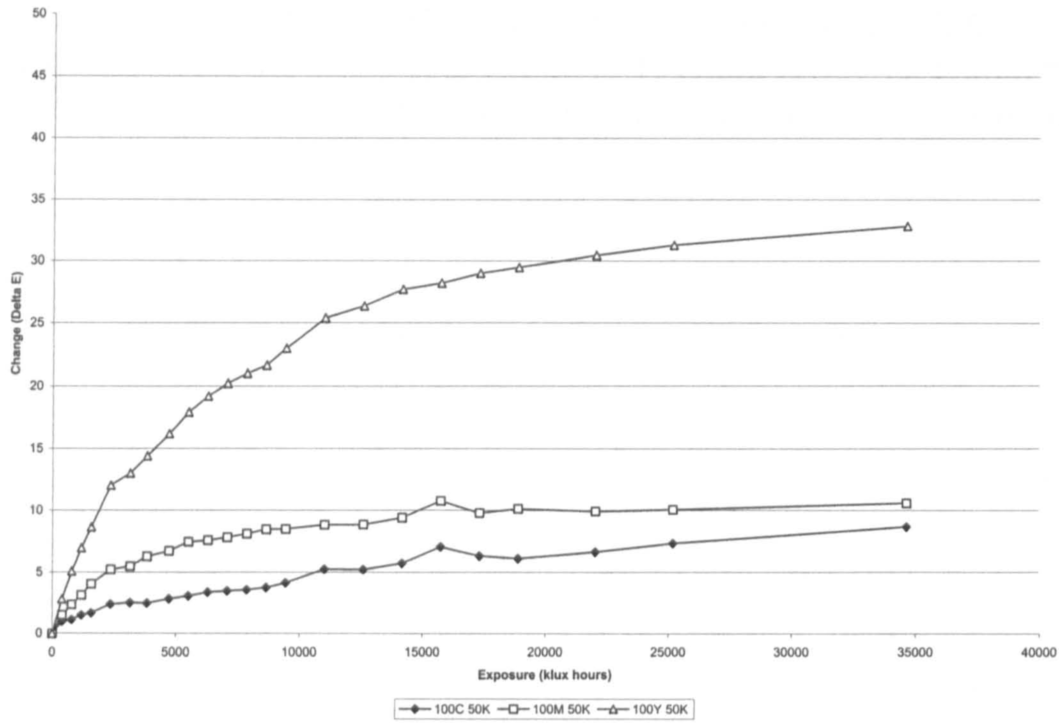
APPENDIX F -Fading rates of the Iris Morgan FA Ink set printed on Somerset Velvet paper (1.1) after exposure to the first Microscal Light Fastness Tester the MBF/U (Mark IV)



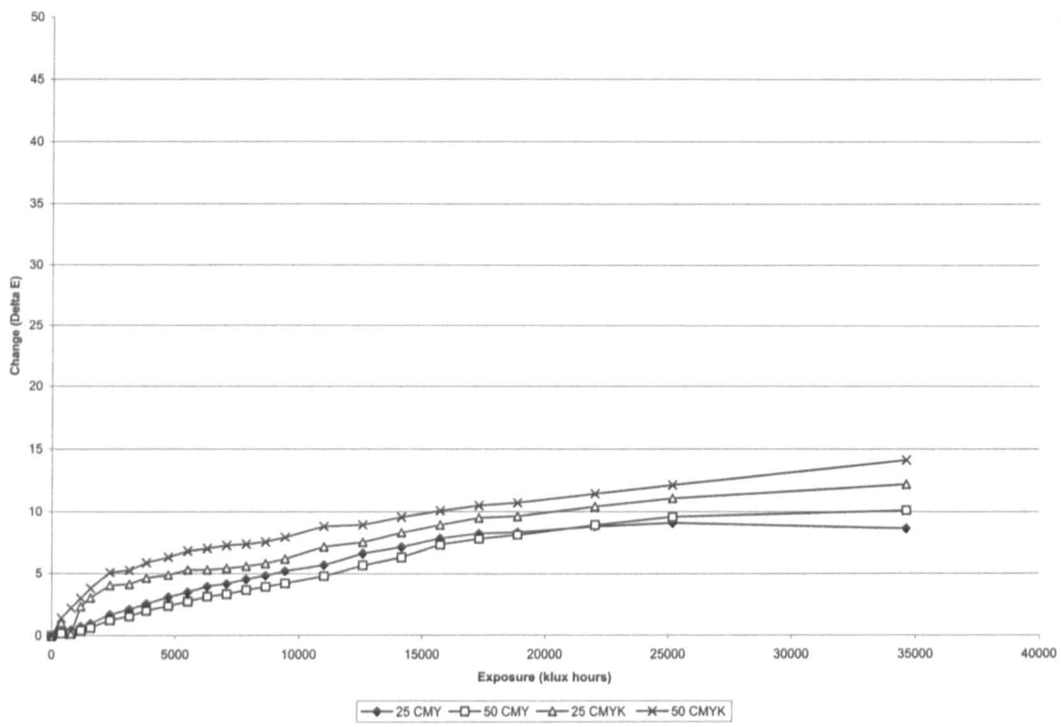
F.1 Plot showing the fading rate of the CMYK ink patches from the Iris Morgan FA ink set printed on Somerset Velvet paper (1.1) after exposure the the high output Microscal Light Fastness Tester.



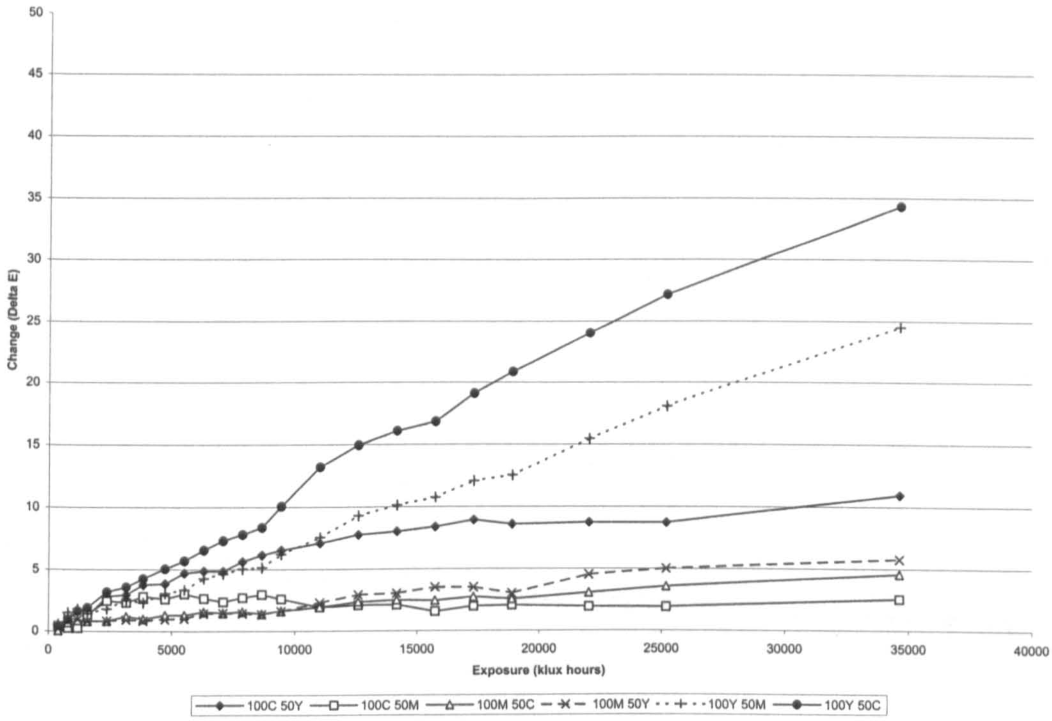
F.2 Plot showing the fading rate of the RGB ink patches from the Iris Morgan FA ink set printed on Somerset Velvet paper (1.1) after exposure the the high output Microscal Light Fastness Tester.



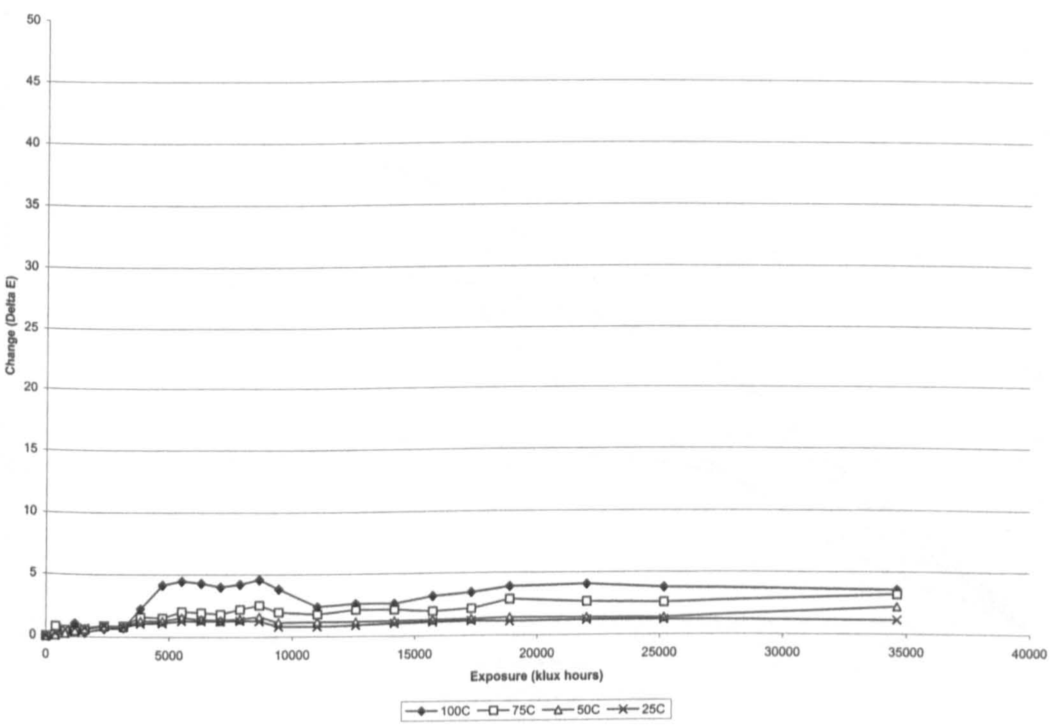
F.3 Plot showing the fading rate of the CMY ink patches printed with 50 % K from the Iris Morgan FA ink set produced on the Somerset Velvet paper (1.1) after exposure the the high output Microscal Light Fastness Tester.



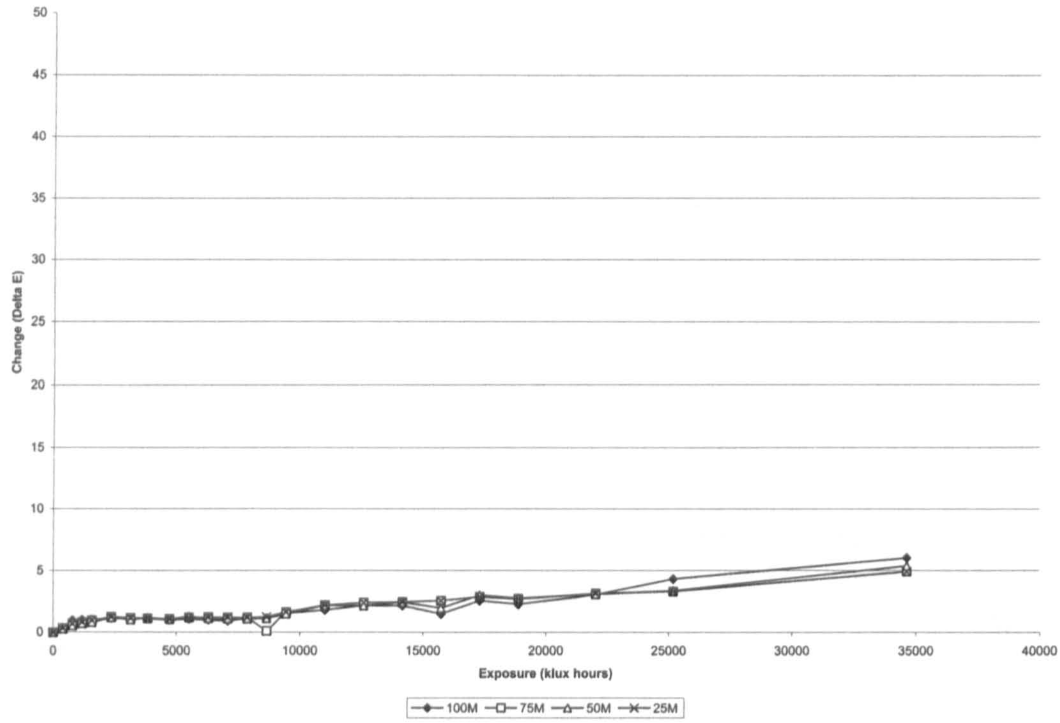
F.4 Plot showing the fading rate of the 25 % and 50 % CMY and CMYK ink patches from the Iris Morgan FA ink set printed on Somerset Velvet paper (1.1) after exposure the the high output Microscal Light Fastness Tester.



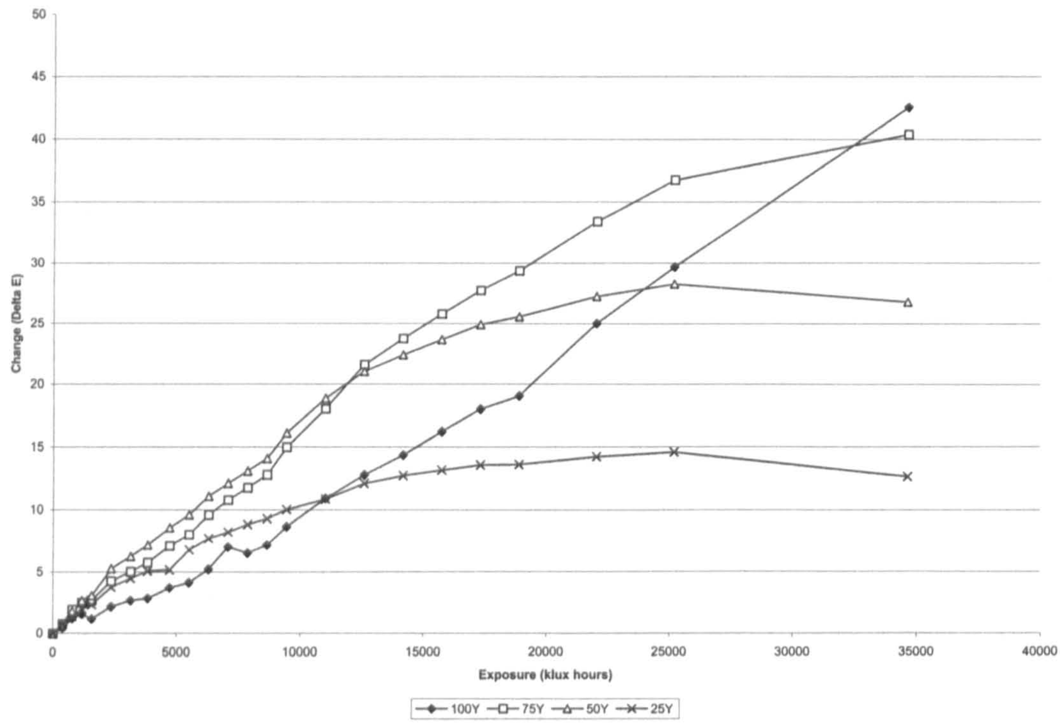
F.5 Plot showing the fading rate of the CMYK ink printed in different combinations from the Iris Morgan FA ink set printed on Somerset Velvet paper (1.1) after exposure the the high output Microscal Light Fastness Tester.



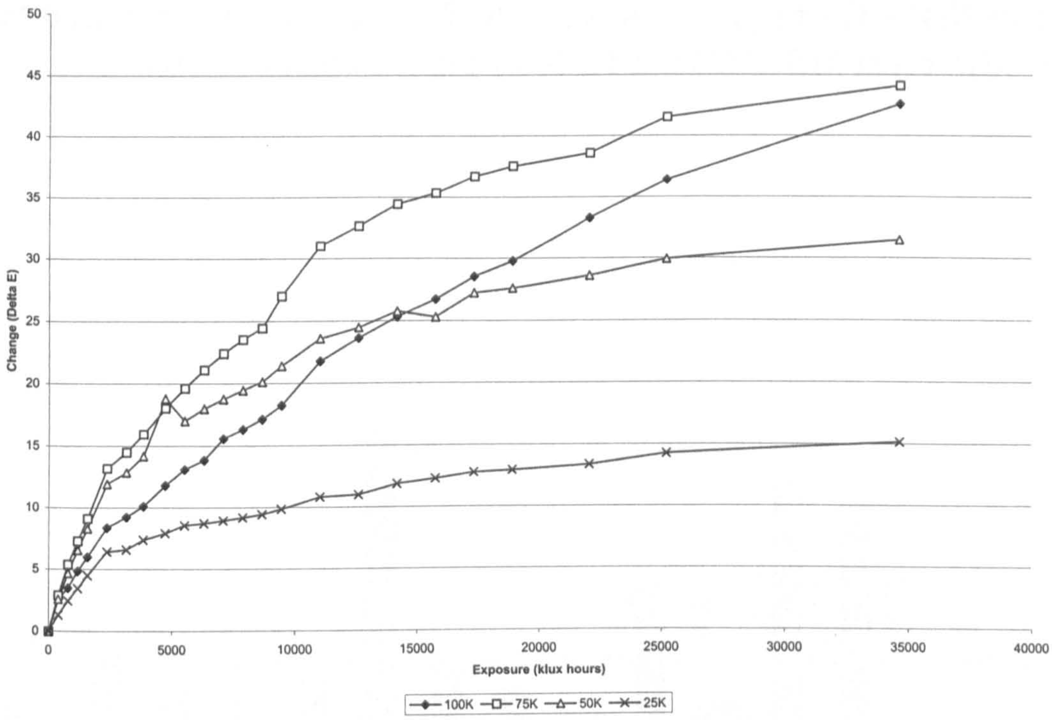
F.6 Plot showing the fading rate of the cyan ink from the Iris Morgan FA ink set printed at different concentrations on Somerset Velvet paper (1.1) after exposure the the high output Microscal Light Fastness Tester.



F.7 Plot showing the fading rate of the magenta ink from the Iris Morgan FA ink set printed at different concentrations on Somerset Velvet paper (1.1) after exposure the the high output Microscal Light Fastness Tester.

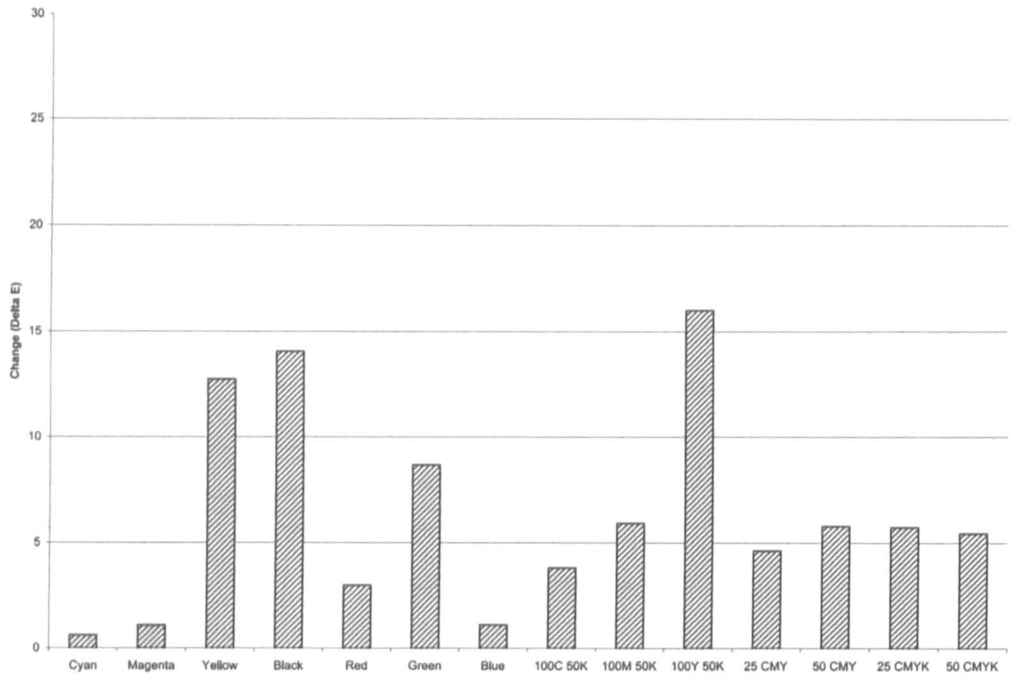


F.8 Plot showing the fading rate of the yellow ink from the Iris Morgan FA ink set printed at different concentrations on Somerset Velvet paper (1.1) after exposure the the high output Microscal Light Fastness Tester.

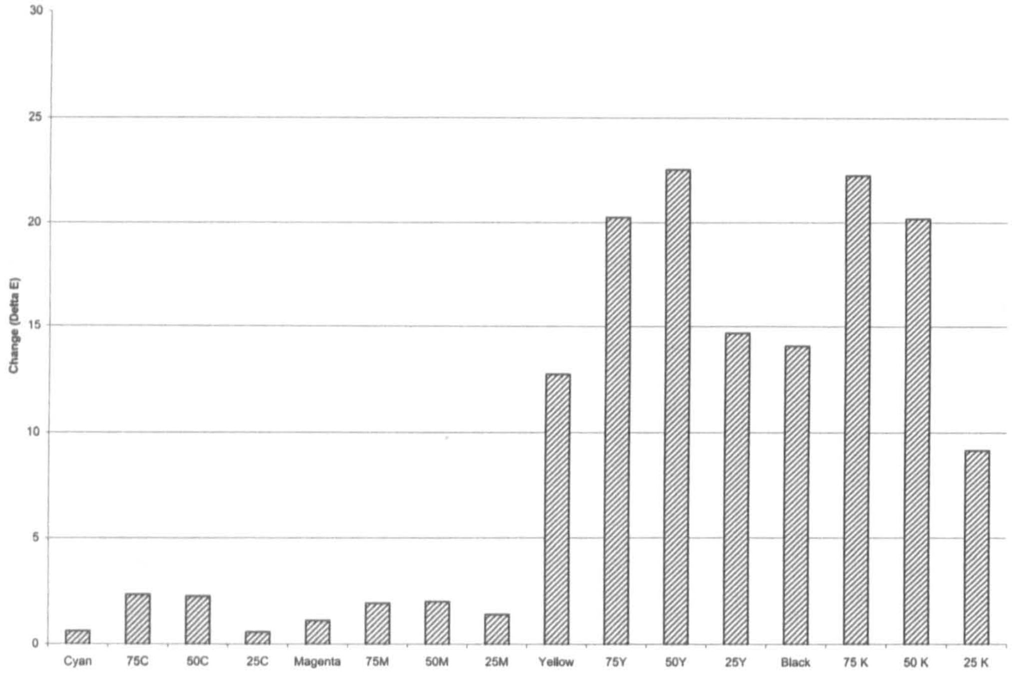


F.9 Plot showing the fading rate of the black ink from the Iris Morgan FA ink set printed at different concentrations on Somerset Velvet paper (1.1) after exposure the the high output Microscal Light Fastness Tester.

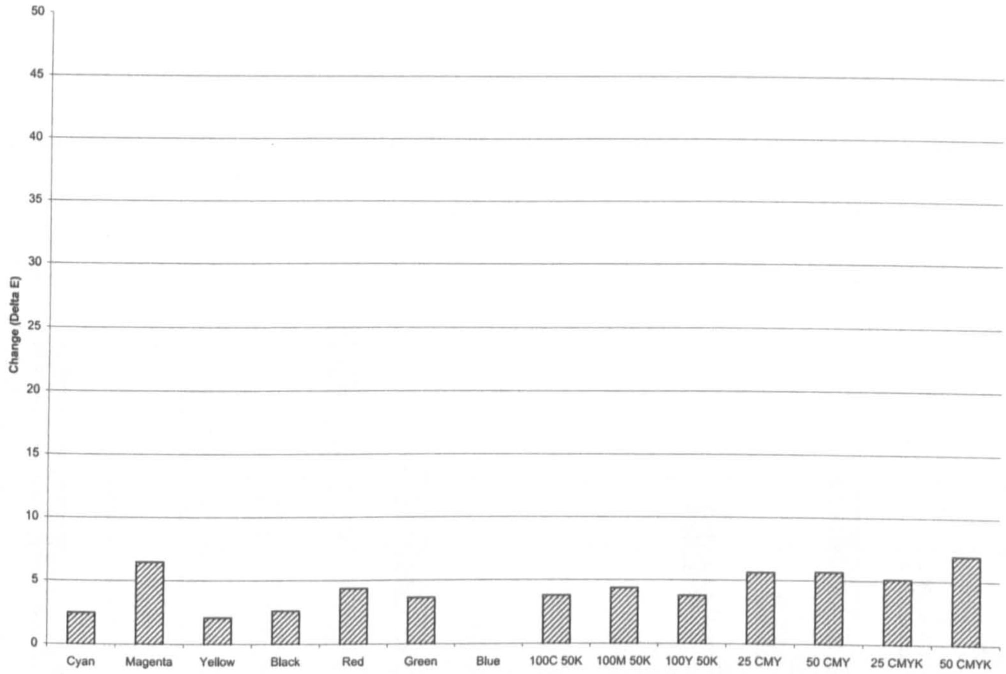
APPENDIX G - Light fastness results for print samples exposed to the Microscal MB/U (Mark 1C R/F) Light Fastness Tester.



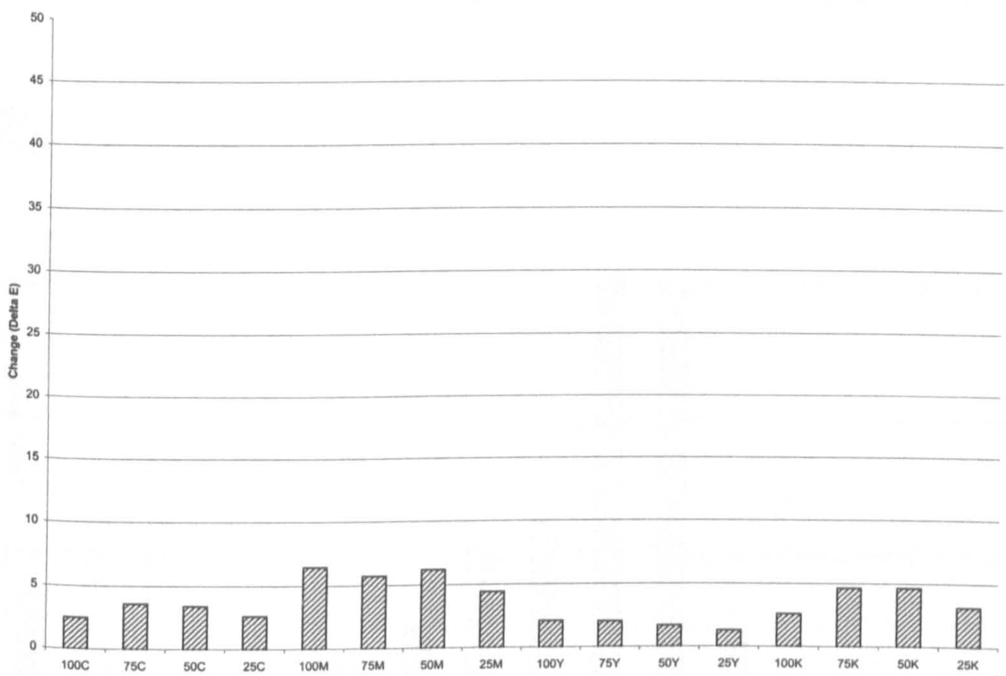
G.1 Bar chart showing the change in ΔEab of the primary ink patches and their colour combinations for the Iris Morgan FA ink set printed on Whatman paper (1.2).



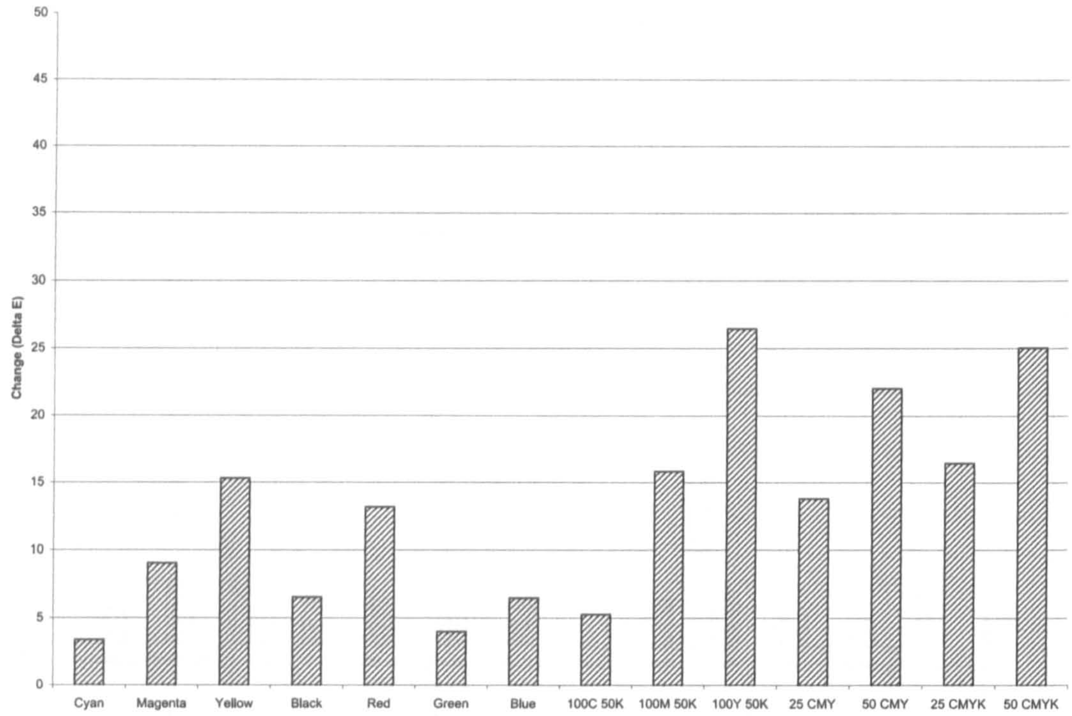
G.2 Bar chart showing the change in Δ Eab of the primary ink patches printed at four different concentrations for the Iris Morgan FA ink set printed on Whatman paper (1.2).



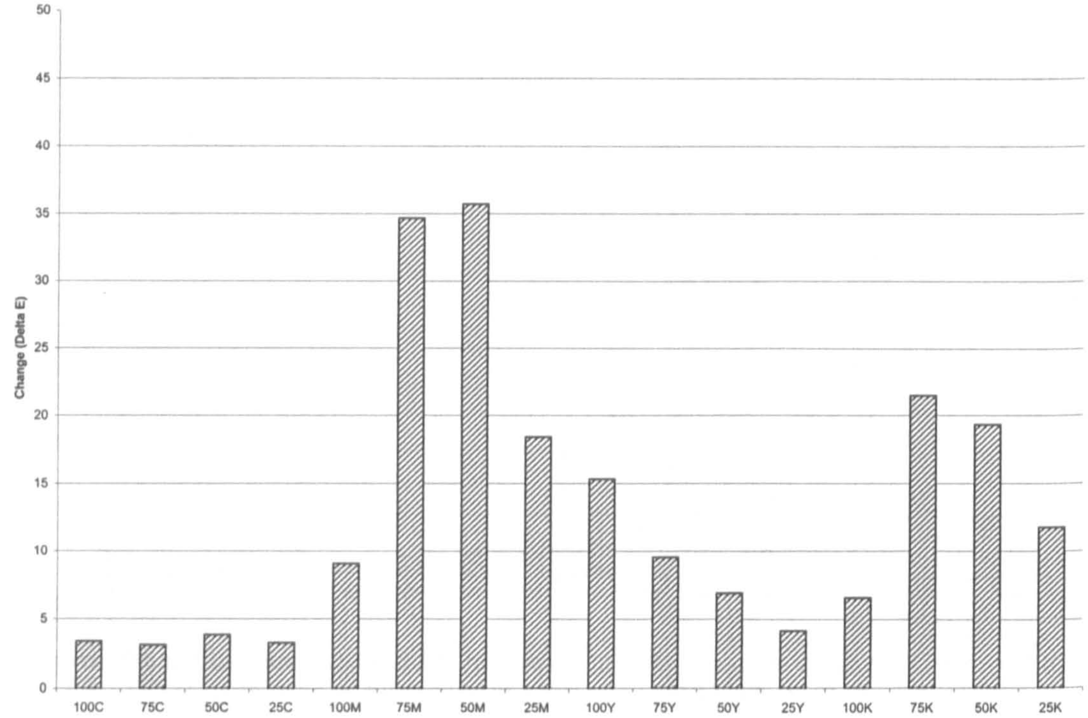
G.3 Bar chart showing the change in ΔEab of the primary ink patches and their colour combinations for the Epson Pro 9000 ink set printed on Epson Photo Glossy paper (3.1).



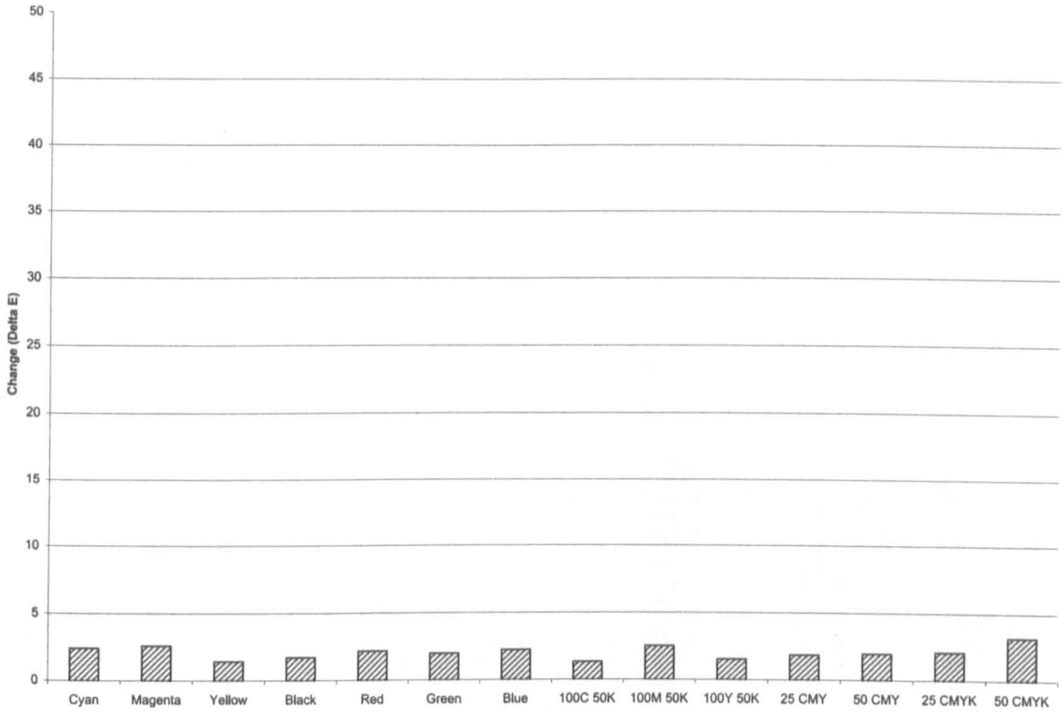
G.4 Bar chart showing the change in ΔEab of the primary ink patches printed at four different concentrations for the Epson Pro 9000 ink set printed on Epson Photo Glossy paper (3.1).



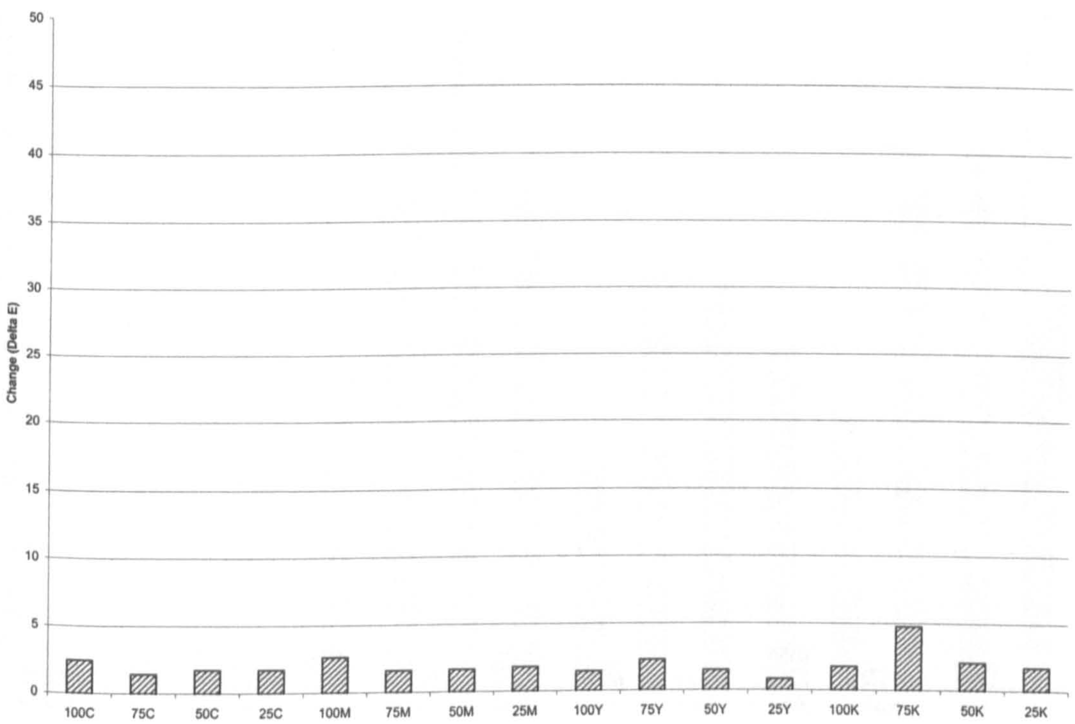
G.5 Bar chart showing the change in ΔEab of the primary ink patches and their colour combinations for the Epson Pro 9000 ink set printed on Epson Presentation Matt paper (3.5).



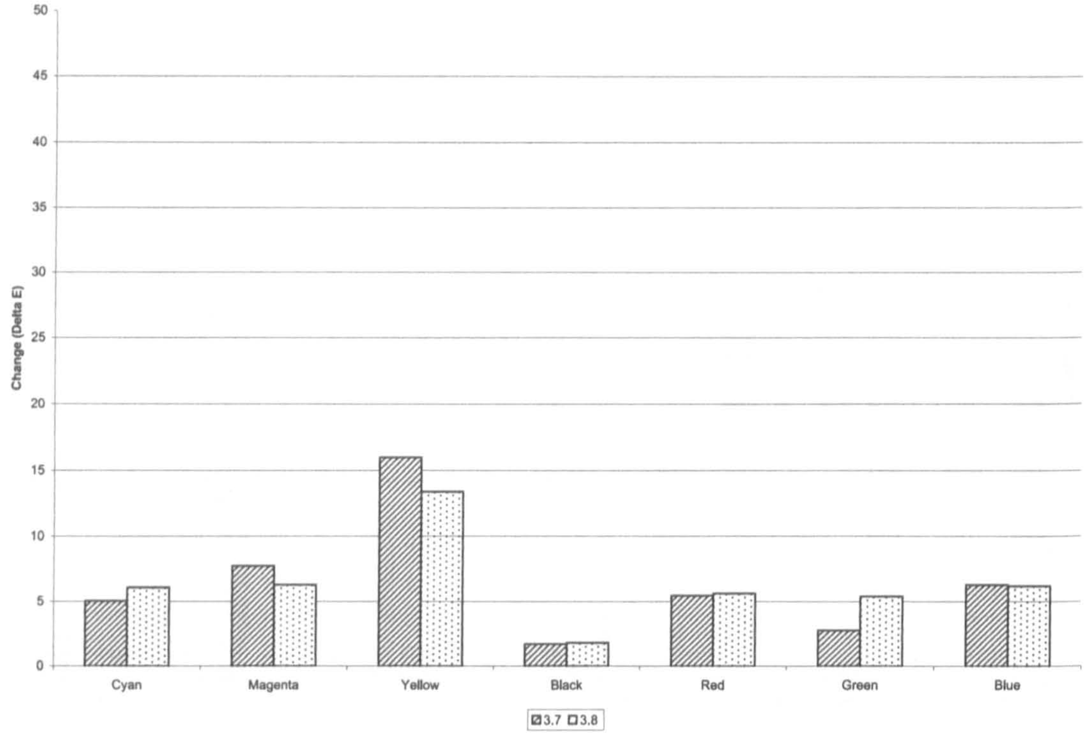
G.6 Bar chart showing the change in ΔEab of the primary ink patches printed at four different concentrations for the Epson Pro 9000 ink set printed on Epson Presentation Matt paper (3.5).



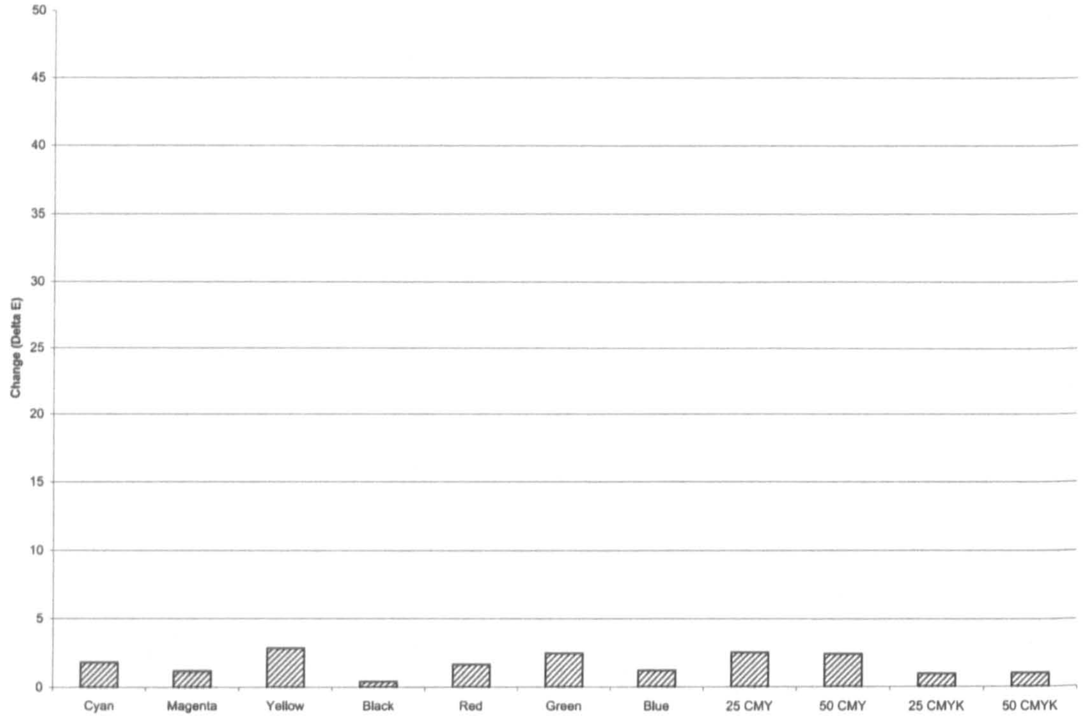
G.7 Bar chart showing the change in ΔEab of the primary ink patches and their colour combinations for the Epson Photo Stylus ink set printed on Epson Photo Stylus Glossy paper (3.6).



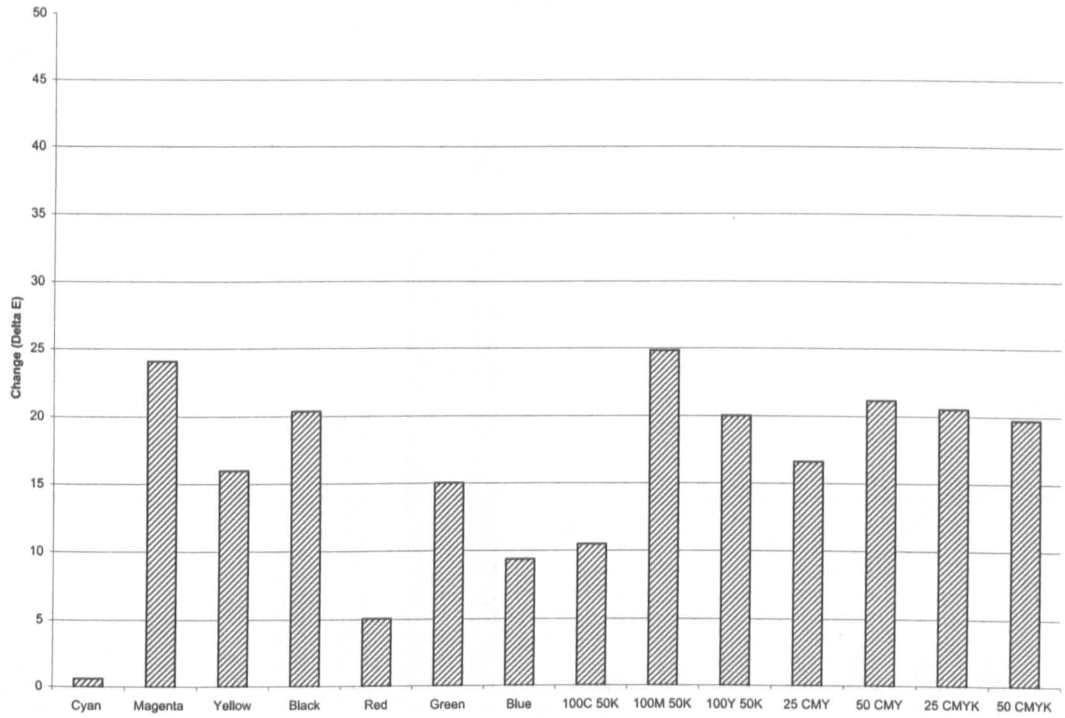
G.8 Bar chart showing the change in ΔEab of the primary ink patches printed at four different concentrations for the Epson Photo Stylus ink set printed on Epson Photo Stylus Glossy paper (3.6)..



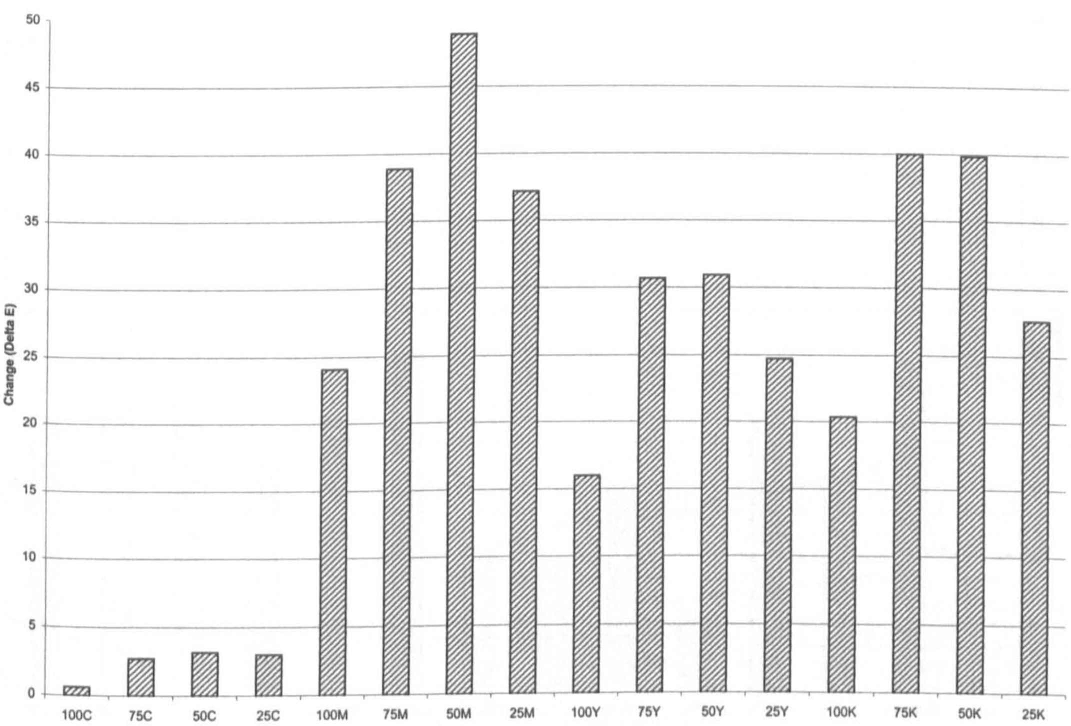
G.9 Bar chart comparing the change in ΔEab of the primary ink patches and their colour combinations of the Epson Pro 9000 ink set printed on Somerset Velvet (3.7) and Whatman watercolour papers (3.8).



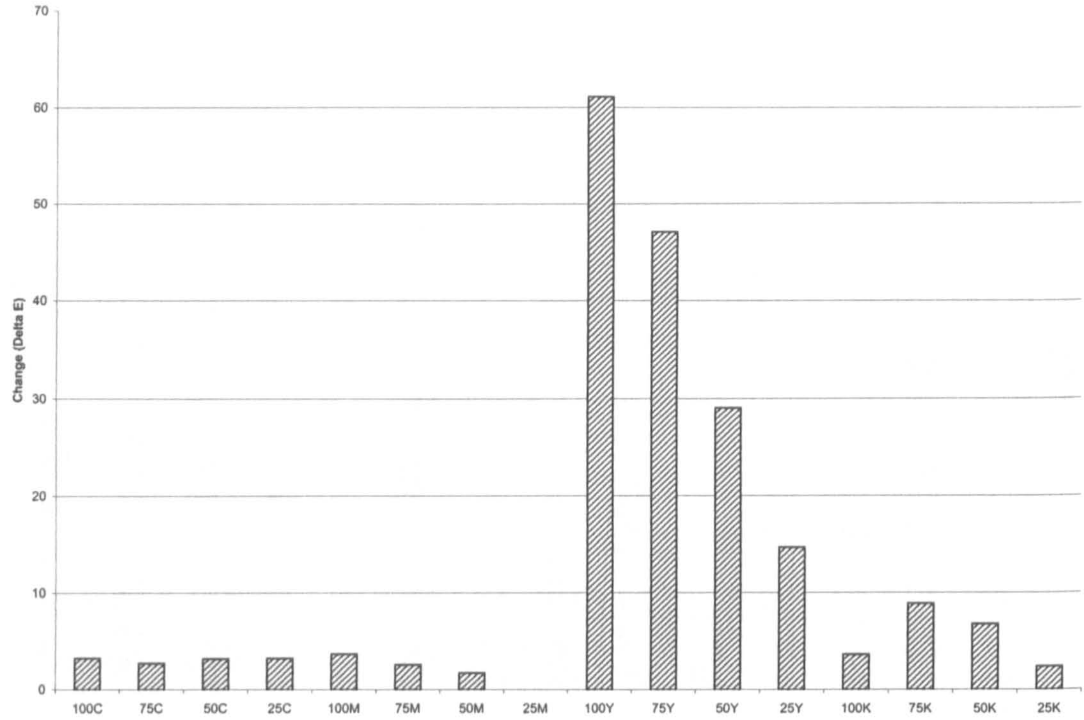
G.10 Bar chart showing the change in ΔEab of the primary ink patches and their colour combinations for the Lysonic ink set printed on Whatman watercolour paper (2.3).



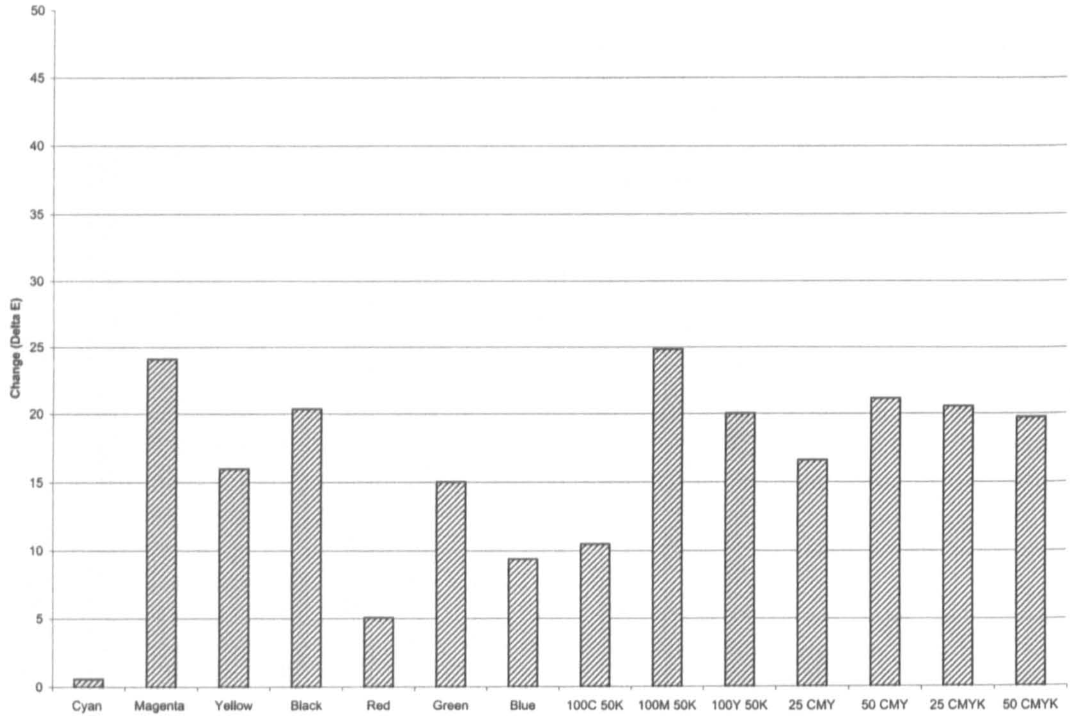
G.11 Bar chart showing the change in ΔEab of the primary ink patches and their colour combinations for the Fotonic ink set printed on Lyson Rough Fine Art paper (2.2)..



G.12 Bar chart showing the change in ΔEab of the primary ink patches printed at four different concentrations for the Fotonic ink set printed on Lyson Rough Fine Art paper (2.2).

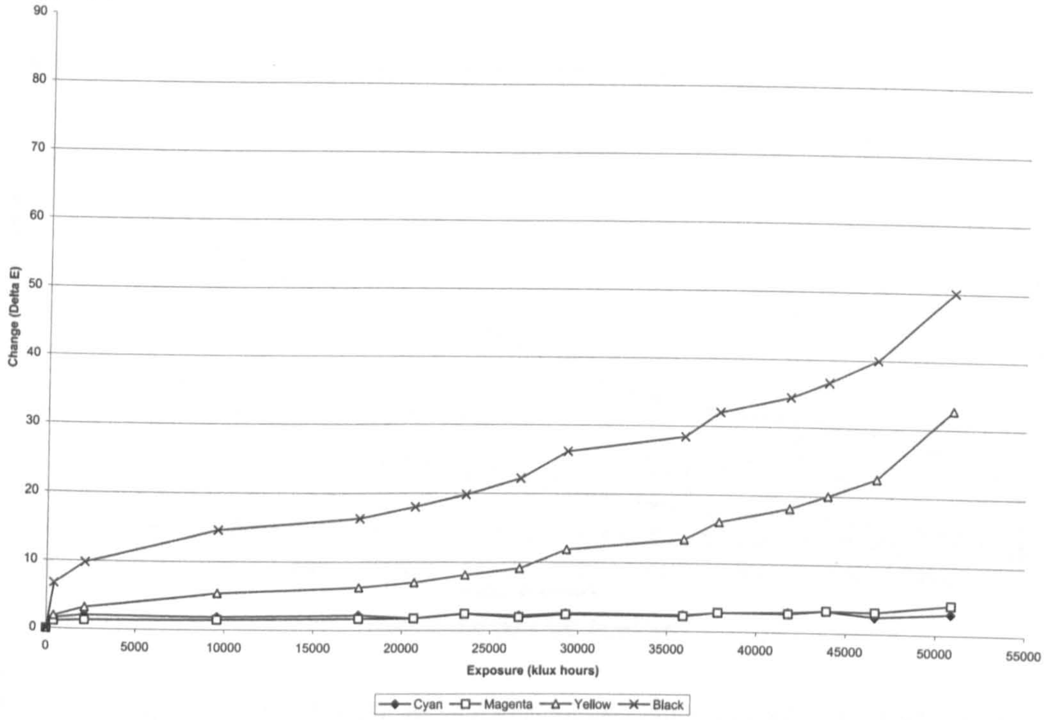


G.13 Bar chart showing the change in ΔEab of the primary ink patches and their colour combinations for the Canon 1500 laser print samples produced on Canon Ultra White paper (5.1).

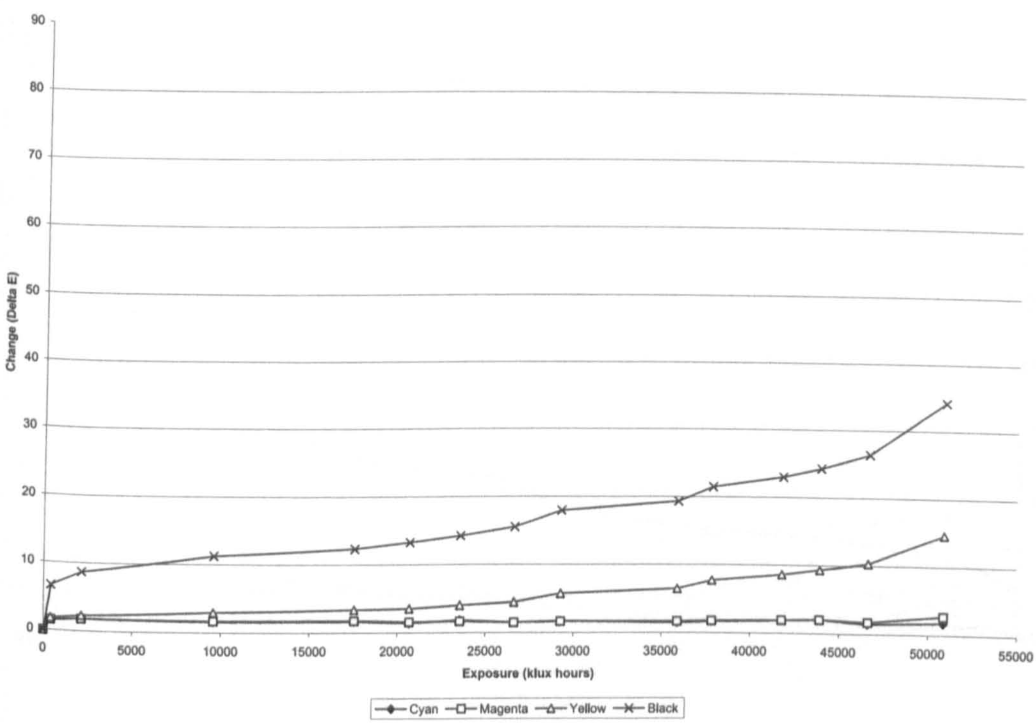


G.14 Bar chart showing the change in ΔEab of the primary ink patches printed at four different concentrations for the Canon 1500 laser print samples produced on Canon Ultra White paper (5.1).

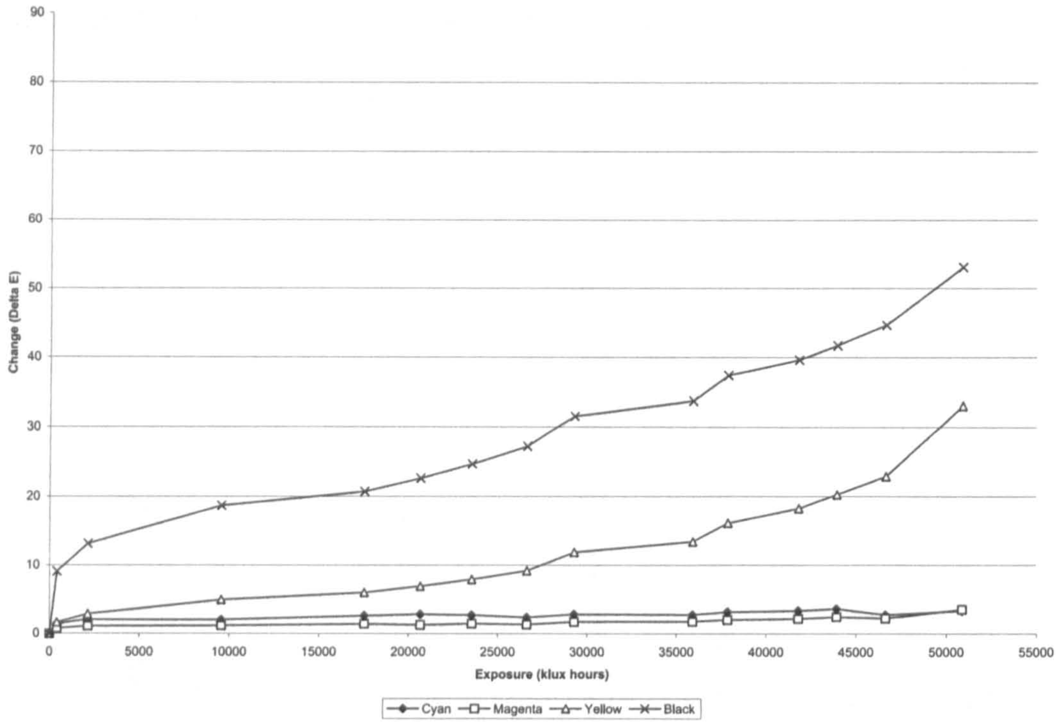
APPENDIX H - Fading rates of the samples exposed to the natural daylight



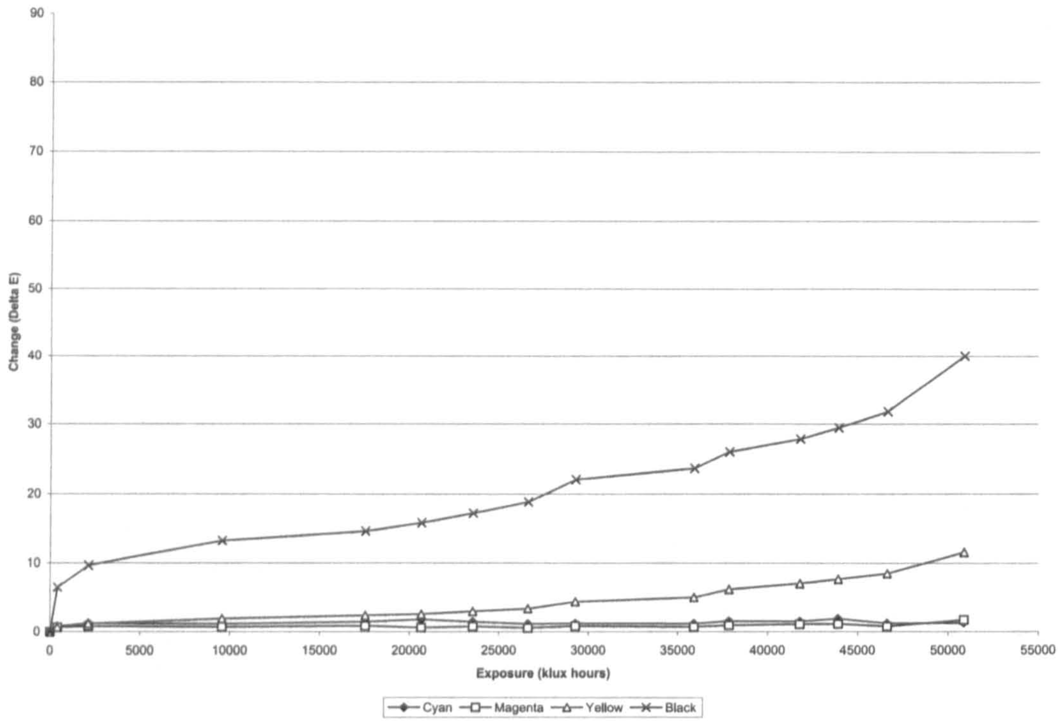
H.1 Plot showing the fading rate of the Iris Morgan FA ink set printed on Somerset paper (1.1) exposed to natural daylight unfiltered.



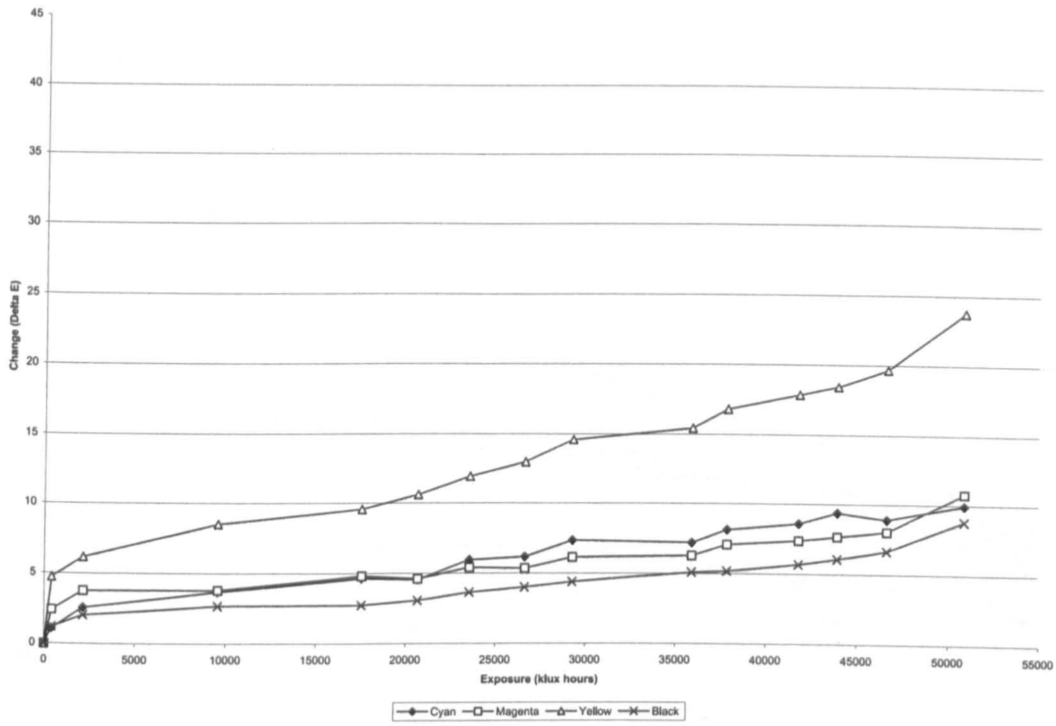
H.2 Plot showing the fading rate of the Iris Morgan FA ink set printed on Somerset paper (1.1) exposed to natural daylight under an UV filter.



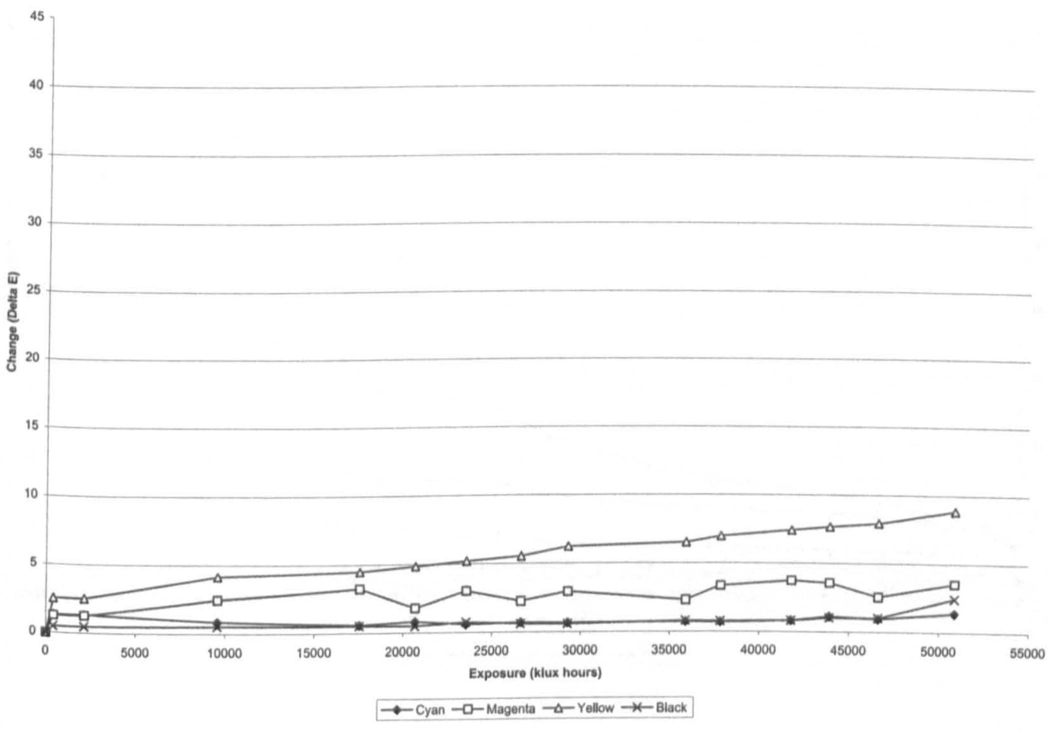
H.3 Plot showing the fading rate of the Iris Morgan FA ink set printed on Whatman paper (1.2) exposed to natural daylight unfiltered.



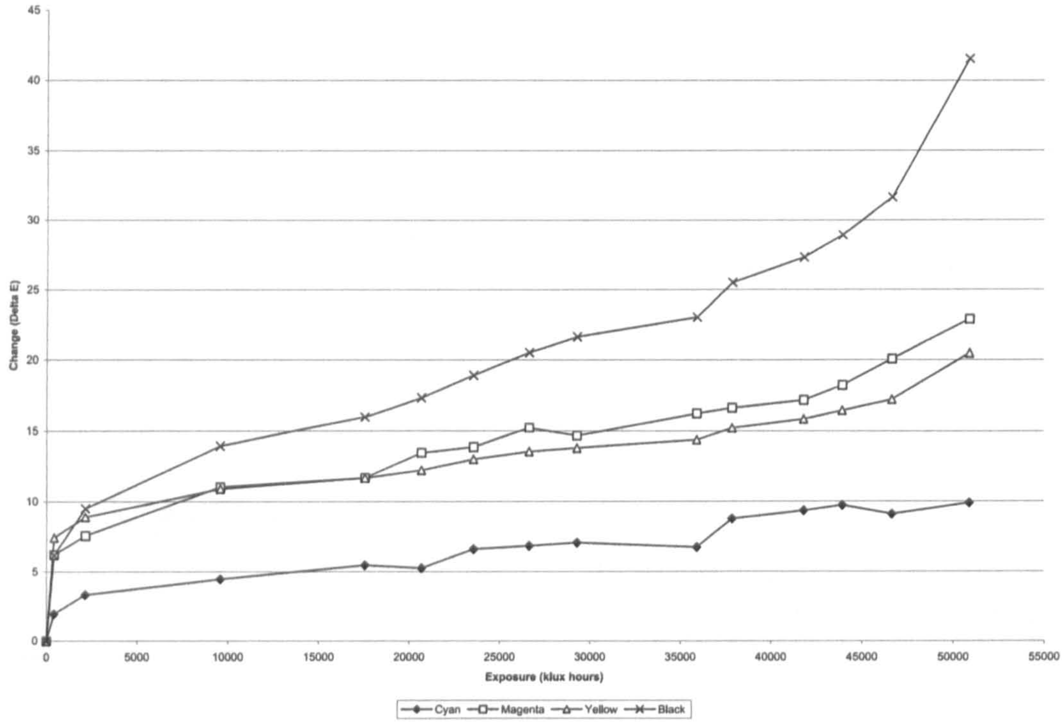
H.4 Plot showing the fading of the Iris Morgan FA ink set printed on Whatman paper (1.2) exposed to natural daylight under an UV filter.



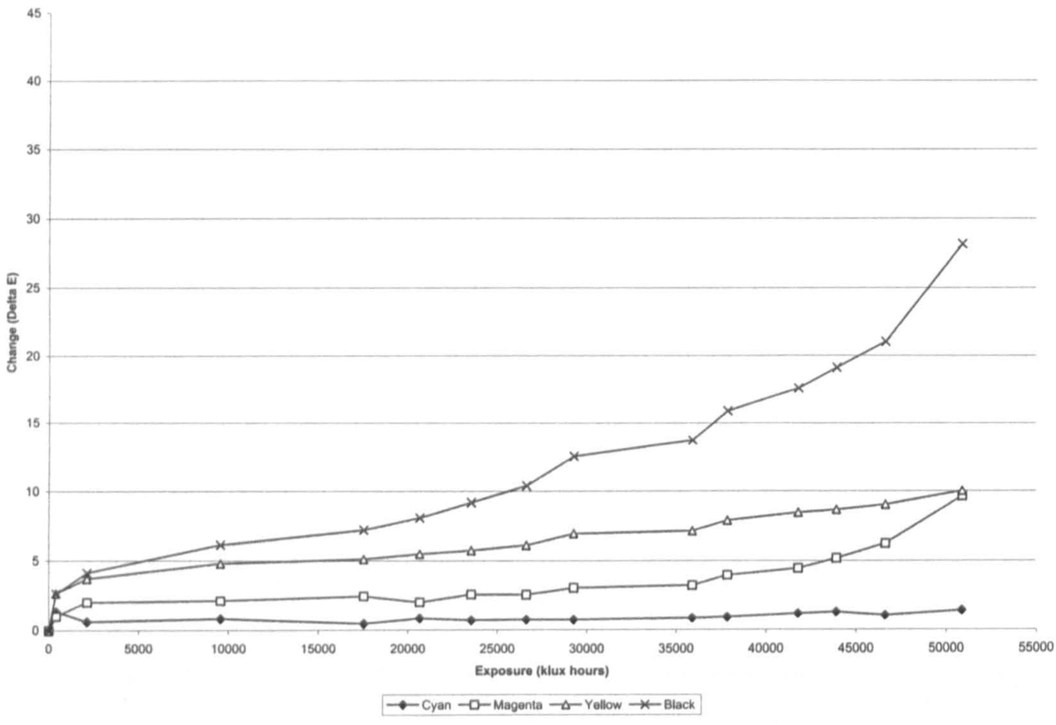
H.5 Plot showing the fading rate of the Lysonic ink set printed on Lyson Soft Fine Art paper (2.1) exposed to natural daylight unfiltered.



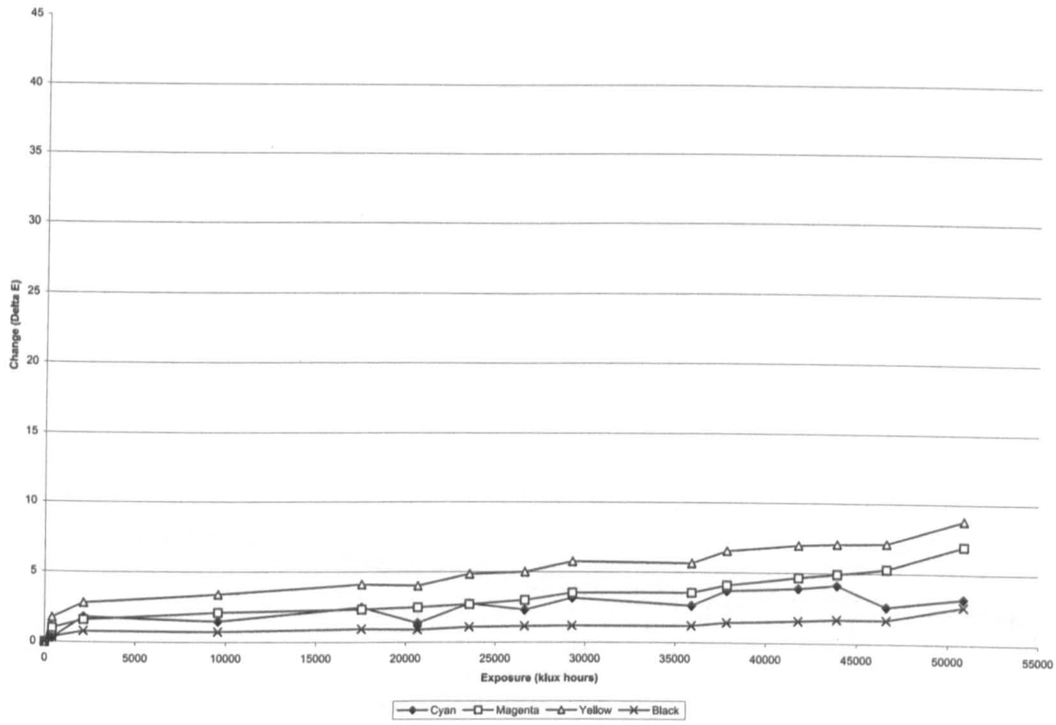
H.6 Plot showing the fading of the Lysonic ink set printed on Lyson Soft Fine Art paper (2.1) exposed to natural daylight under an UV filter.



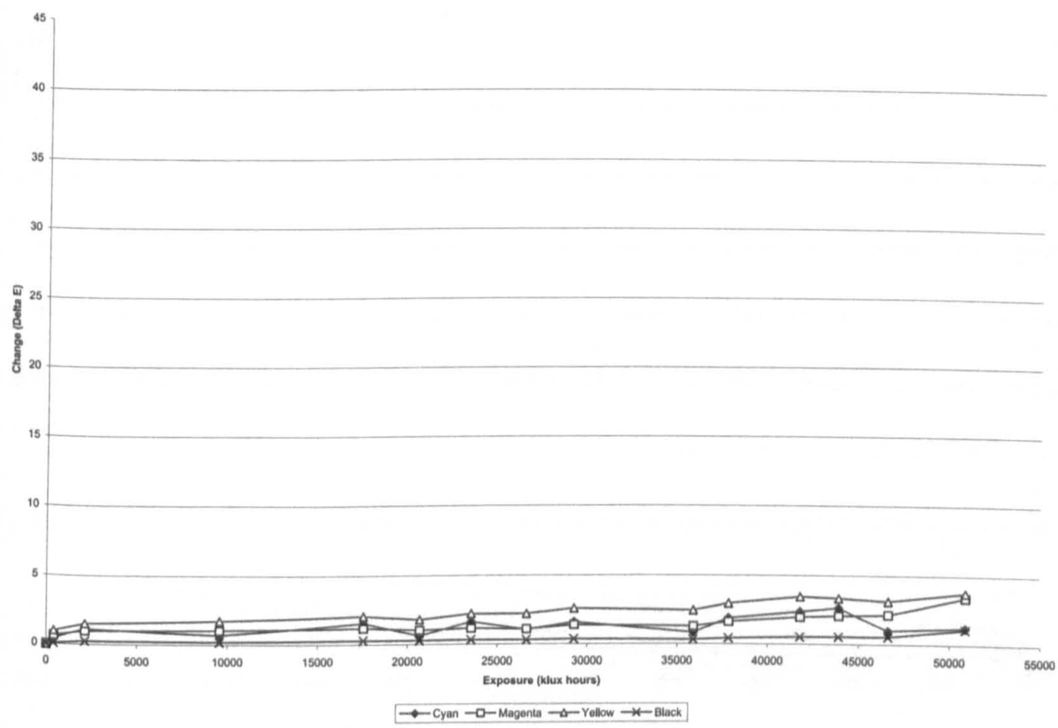
H.7 Plot showing the fading rate of the Fotonic ink set printed on Lysonic Rough Fine Art paper (2.2) exposed to natural daylight unfiltered.



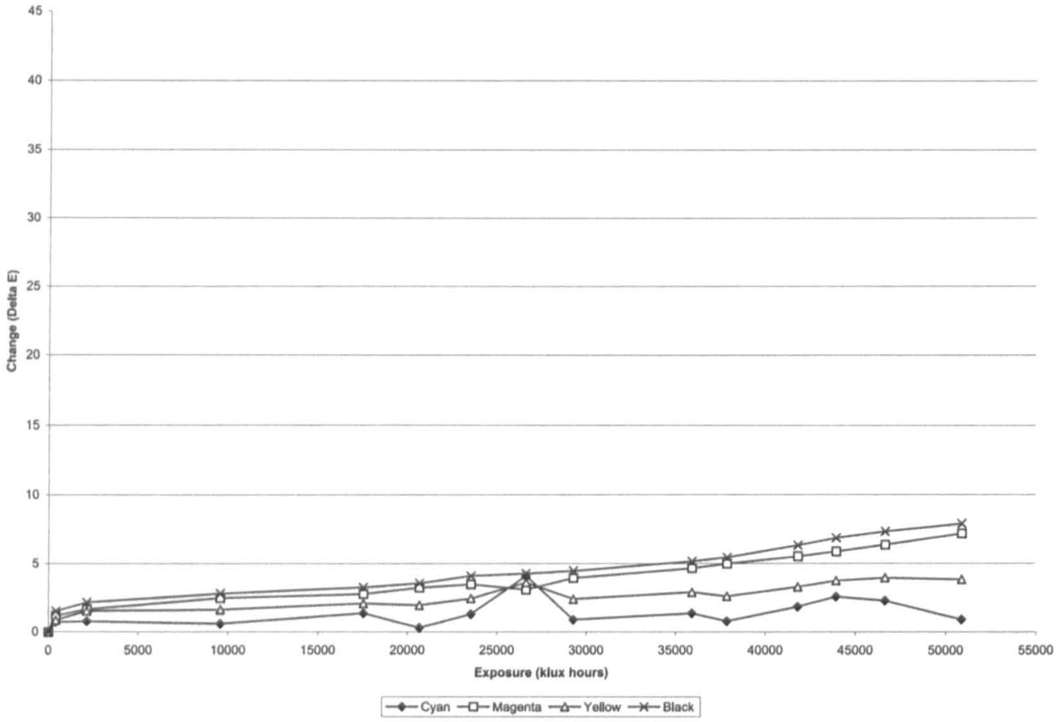
H.8 Plot showing the fading of the Fotonic ink set printed on Lyson Rough Fine Art paper (2.2) exposed to natural daylight under an UV filter.



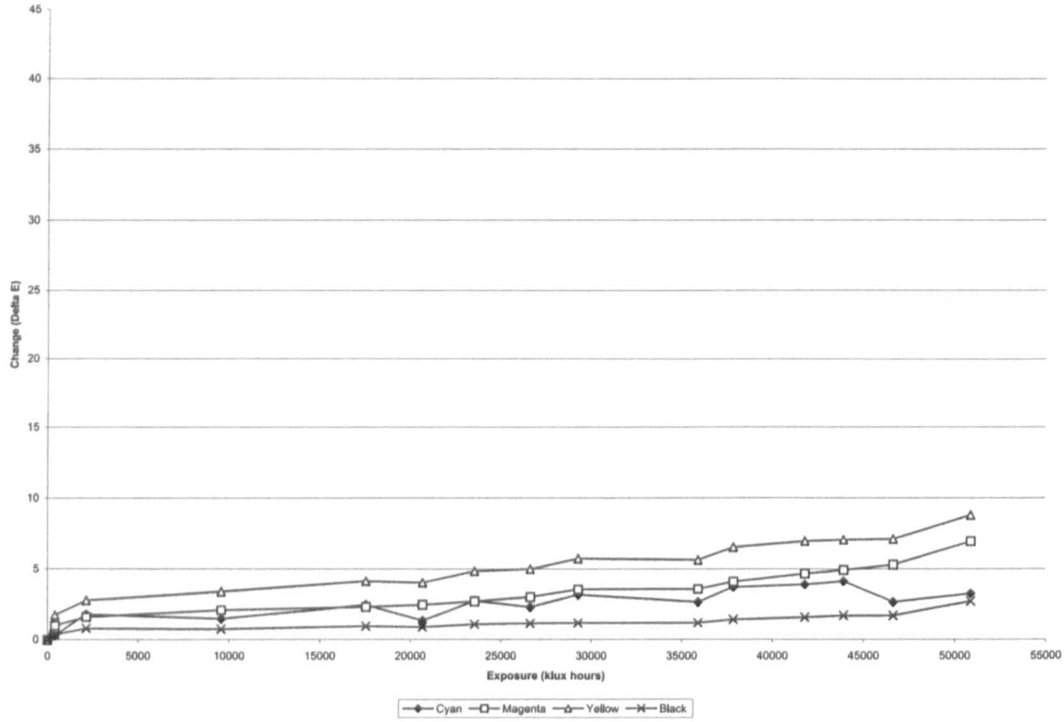
H.9 Plot showing the fading rate of the Lysonic ink set printed on Whatman paper (2.3) exposed to natural daylight unfiltered.



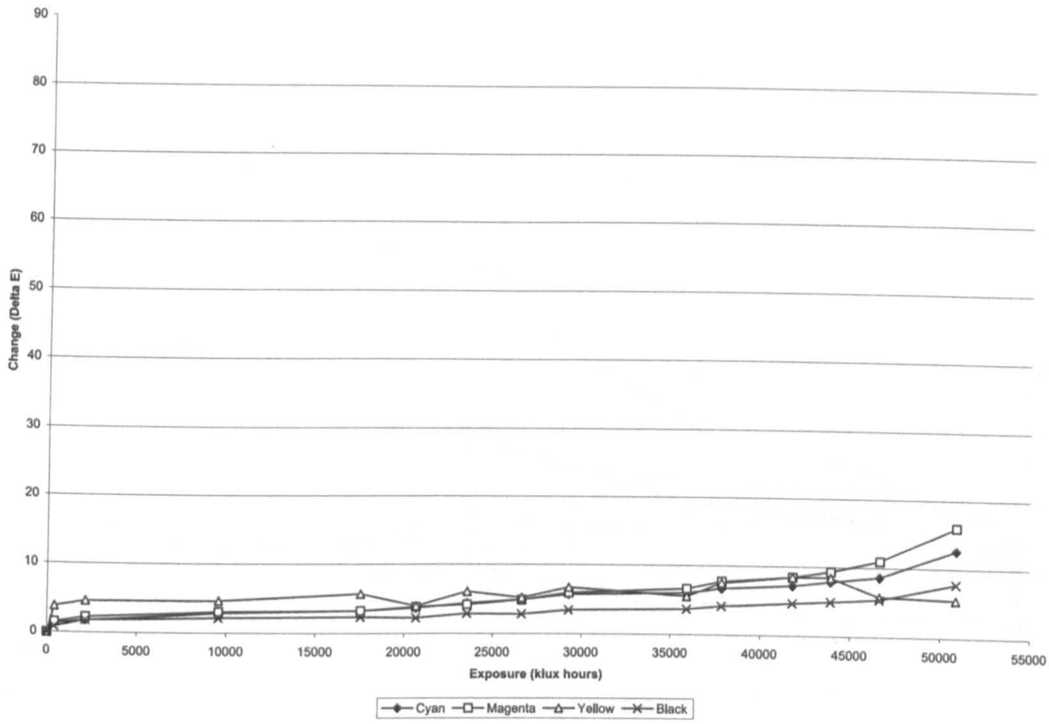
H.10 Plot showing the fading of the Lysonic ink set printed on Whatman paper (2.3) exposed to natural daylight under an UV filter.



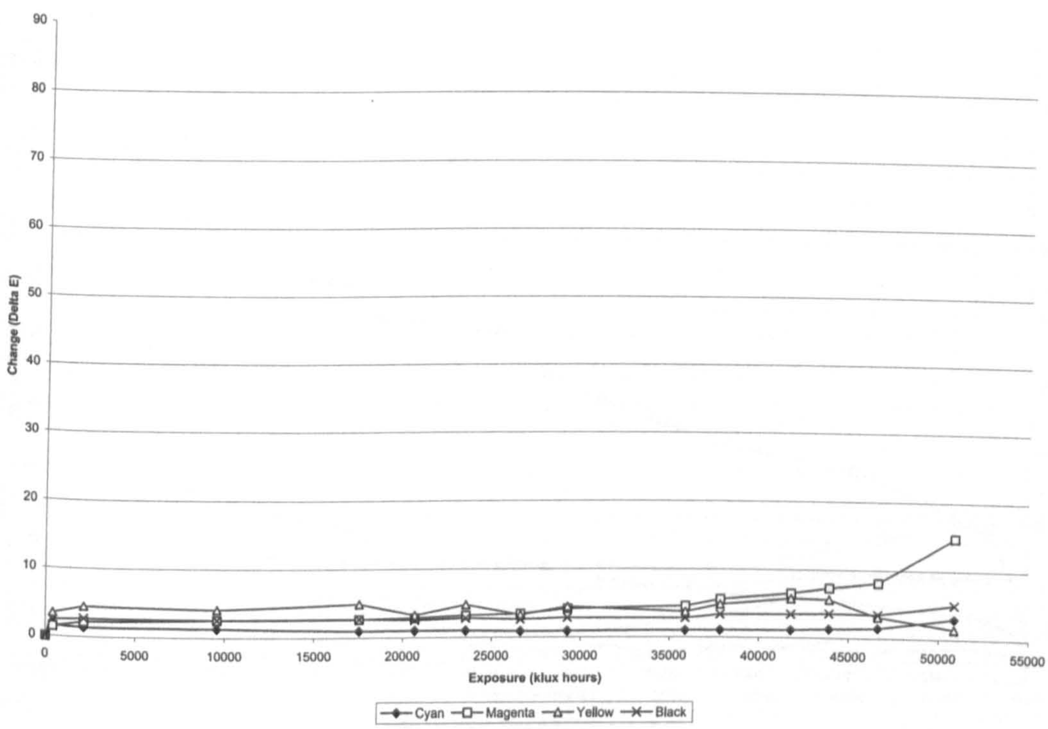
H.11 Plot showing the fading rate of the Epson Pro 9000 ink set printed on Epson Photo Glossy paper (3.1) exposed to natural daylight unfiltered.



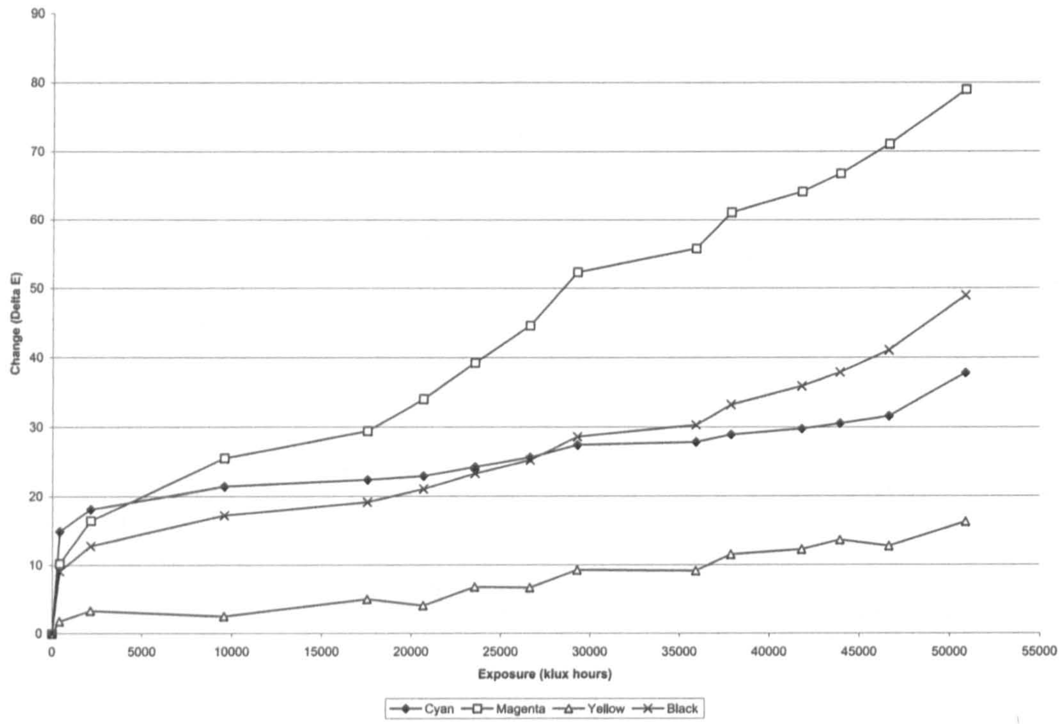
H.12 Plot showing the fading rate of the Epson Pro 9000 ink set printed on Epson Photo Glossy paper (3.1) exposed to natural daylight under an UV filter.



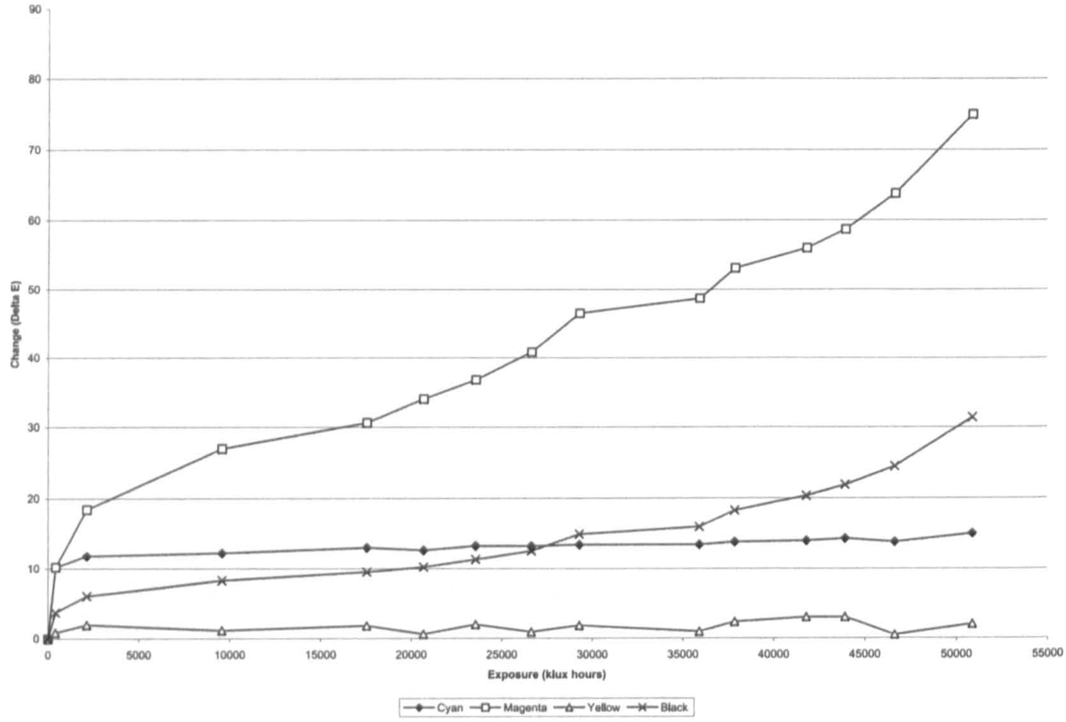
H.13 Plot showing the fading rate of the Epson Pro 9000 ink set printed on Somerset paper (3.3) exposed to natural daylight unfiltered.



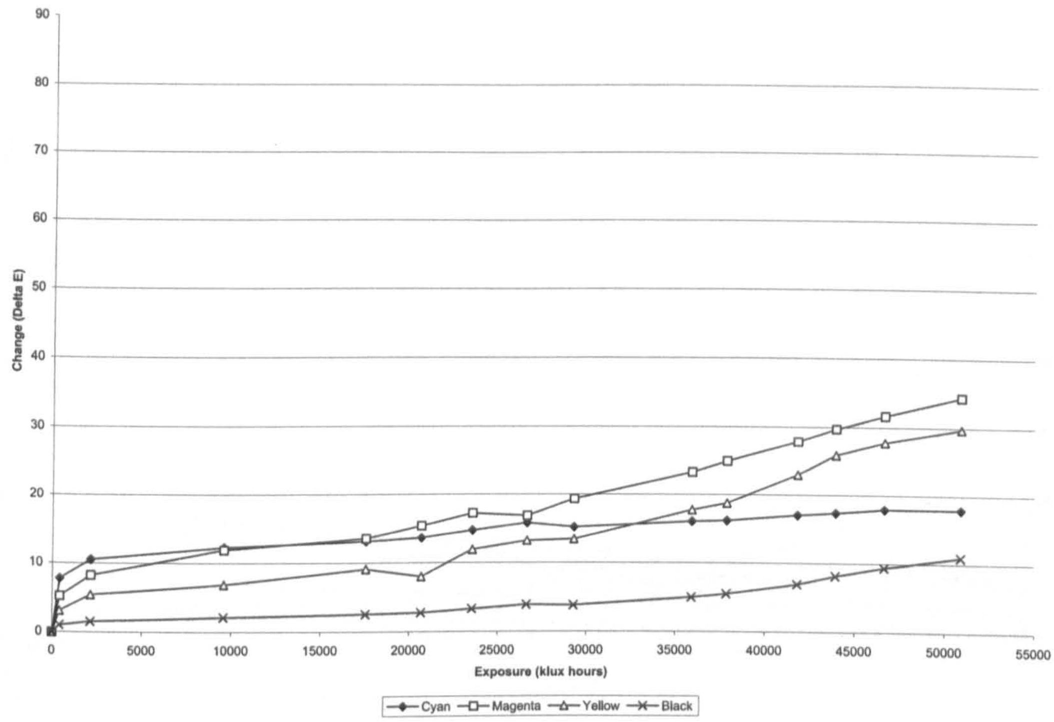
H.14 Plot showing the fading rate of the Epson Pro 9000 ink set printed on Somerset paper (3.3) exposed to natural daylight under an UV filter.



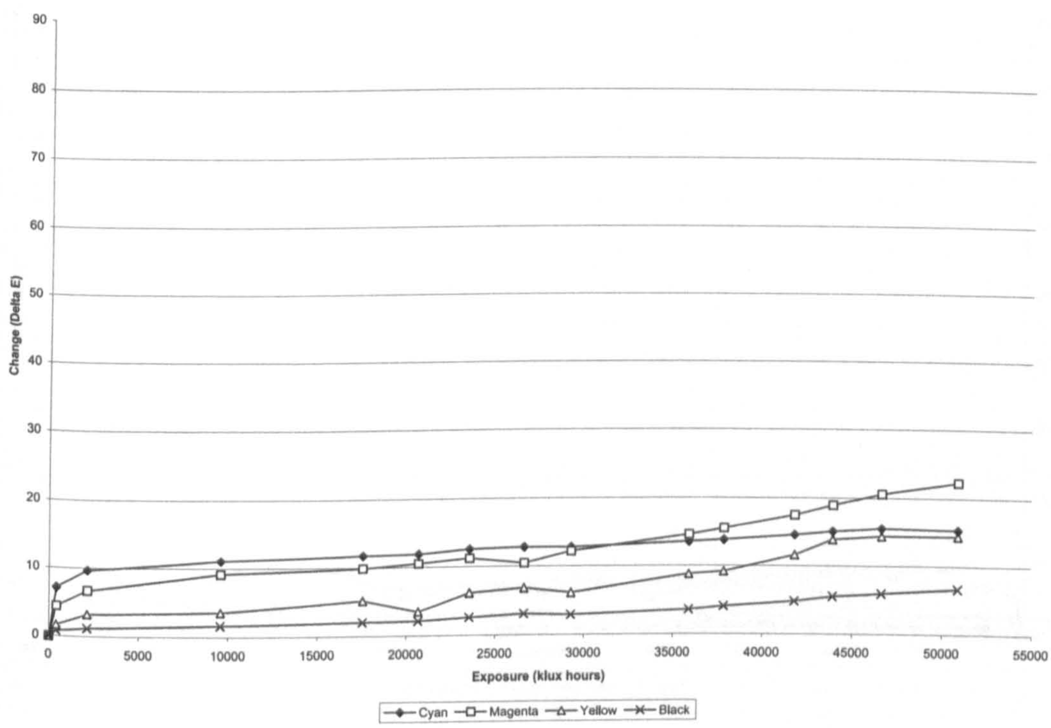
H.15 Plot showing the fading rate of the Epson Pro 9000 ink set printed on Whatman paper (3.4) exposed to natural daylight unfiltered.



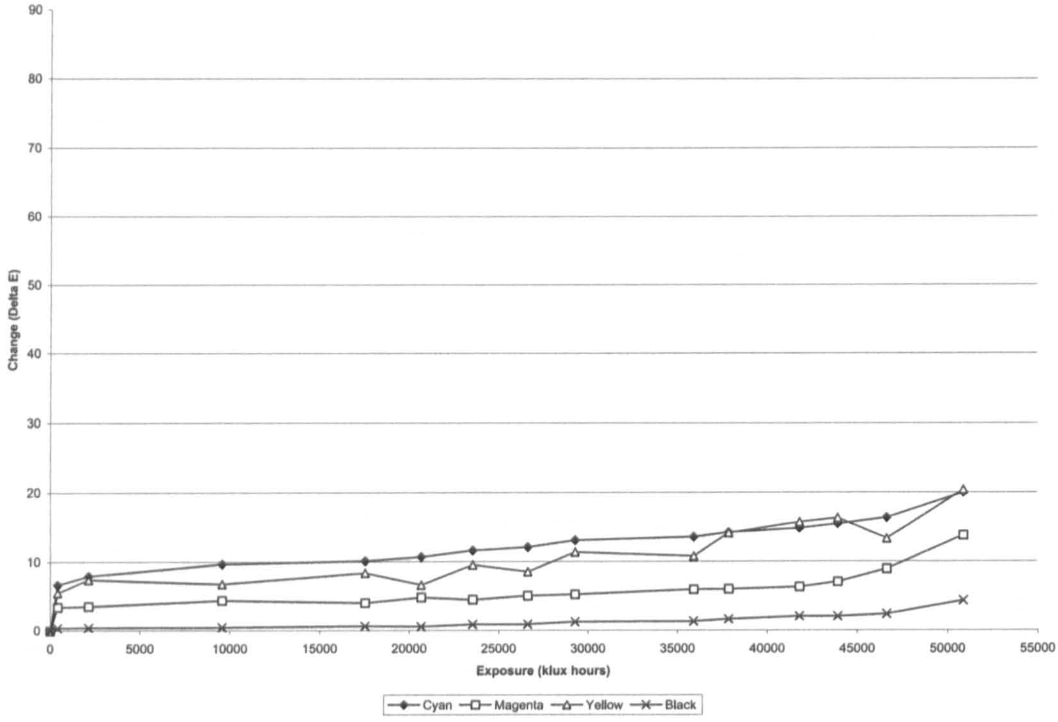
H.16 Plot showing the fading rate of the Epson Pro 9000 ink set printed on Whatman paper (3.4) exposed to natural daylight under an UV filter.



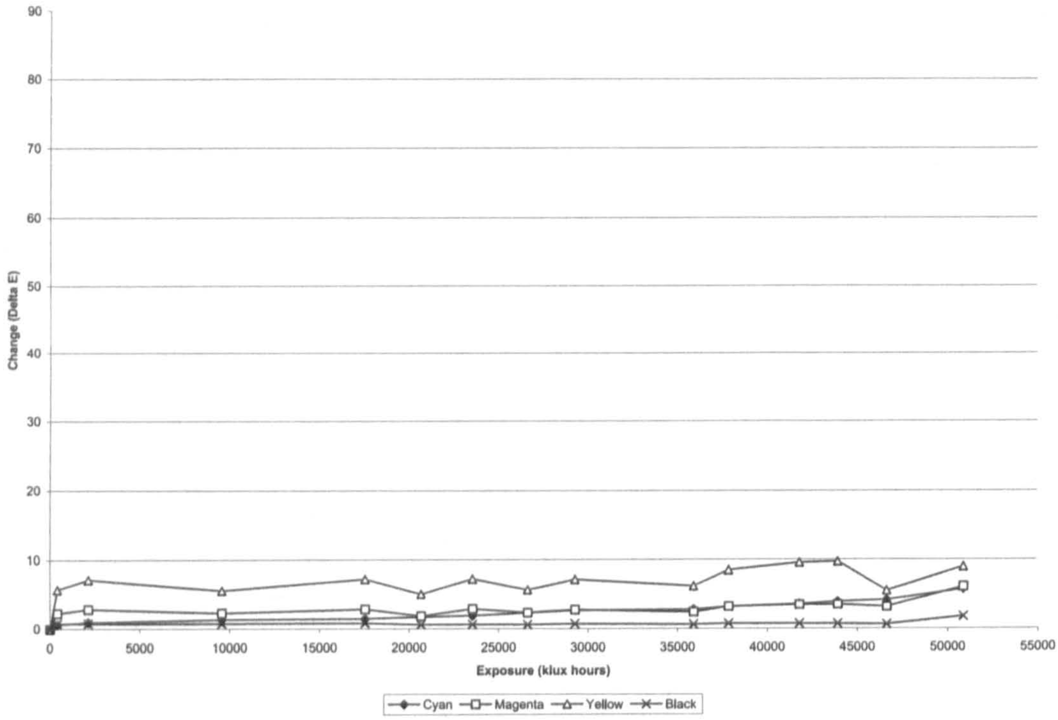
H.17 Plot showing the fading rate of the Epson Photo Stylus ink set printed on Epson Photo Glossy paper (3.6) exposed to natural daylight unfiltered.



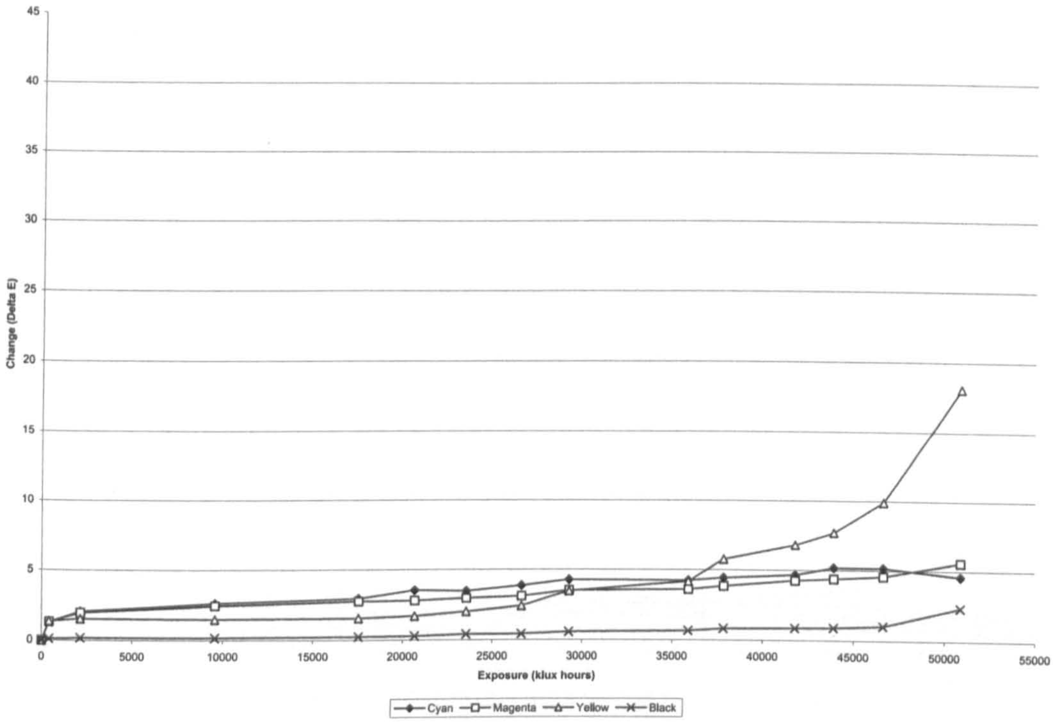
H.18 Plot showing the fading rate of the Epson Photo Stylus ink set printed on Epson Photo Glossy paper (3.6) exposed to natural daylight under an UV filter.



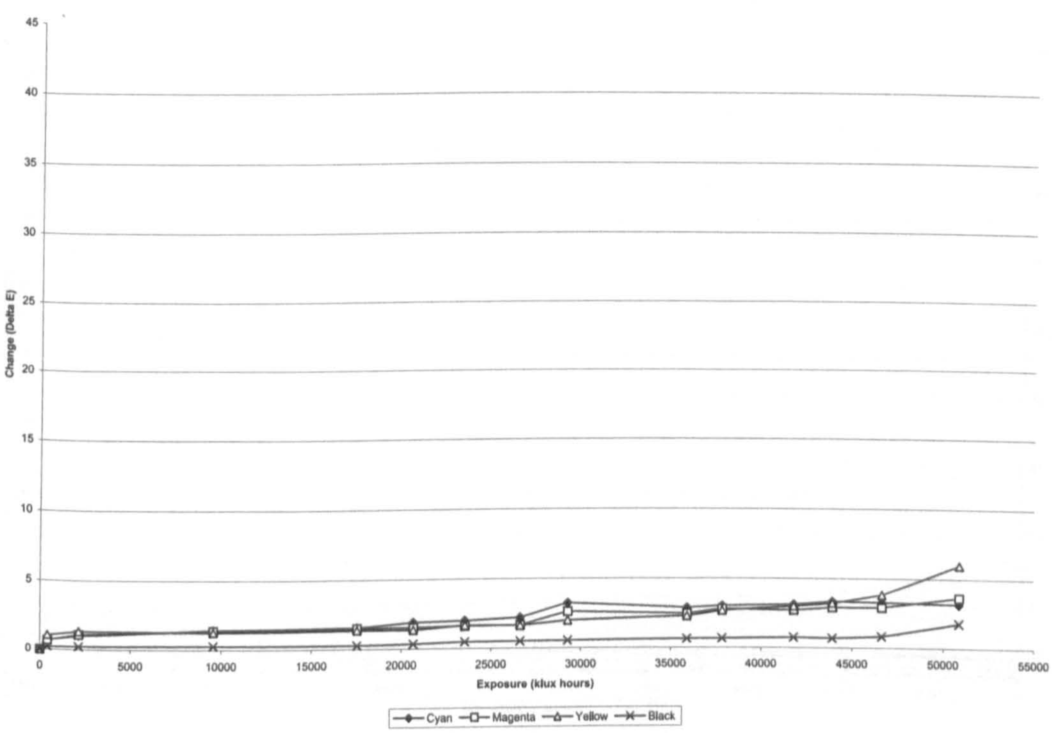
H.19 Plot showing the fading rate of the Canon 1500 laser samples printed on Canon Ultra White paper (5.1) exposed to natural daylight unfiltered.



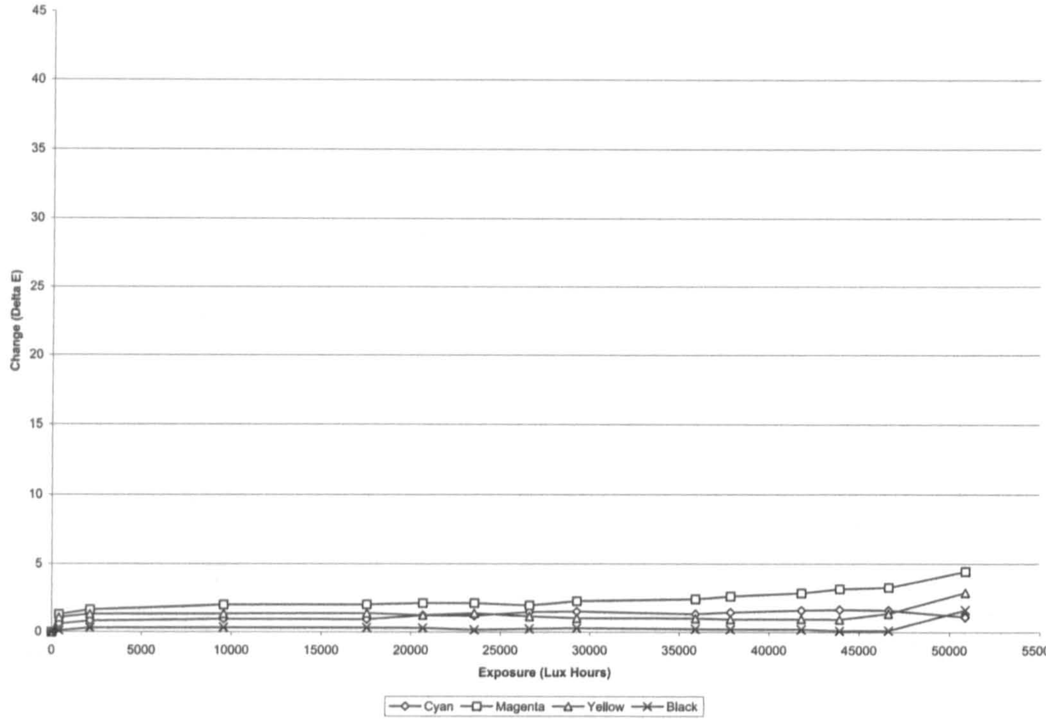
H.20 Plot showing the fading rate of the Canon 1150 laser samples printed on Canon Ultra White paper (5.1) exposed to natural daylight under an UV filter.



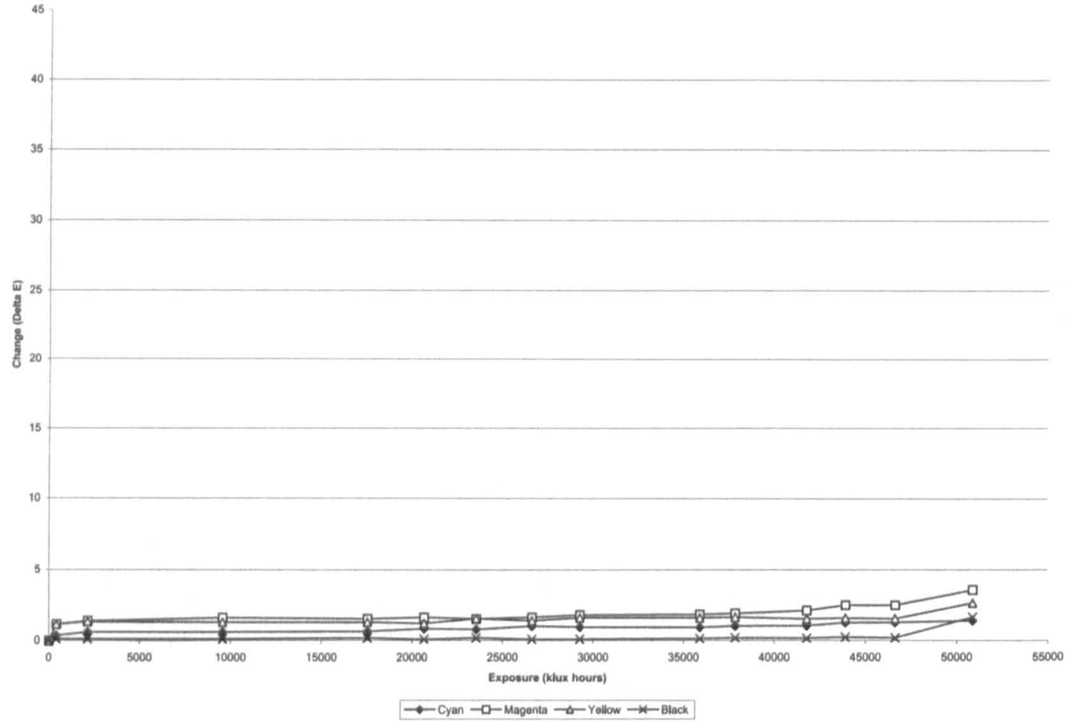
H.21 Plot showing the fading rate of the Canon 1150 laser samples printed on Canon Card (5.2) exposed to natural daylight unfiltered.



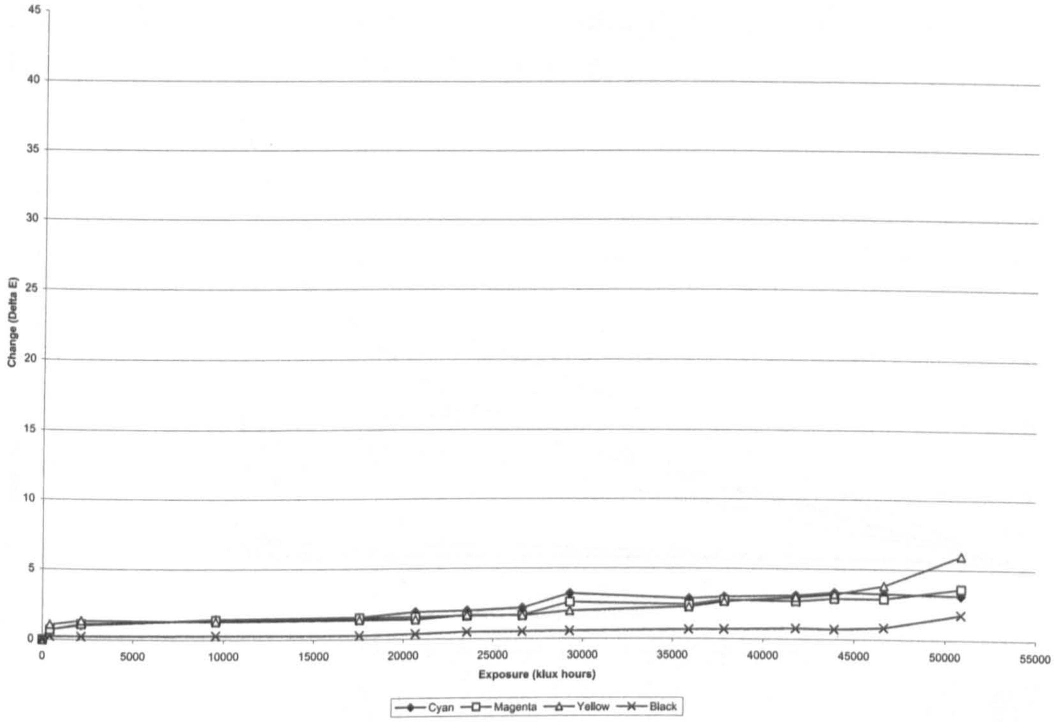
H.22 Plot showing the fading rate of the Canon 1150 laser samples printed on Canon Card (5.2) exposed to natural daylight under an UV filter.



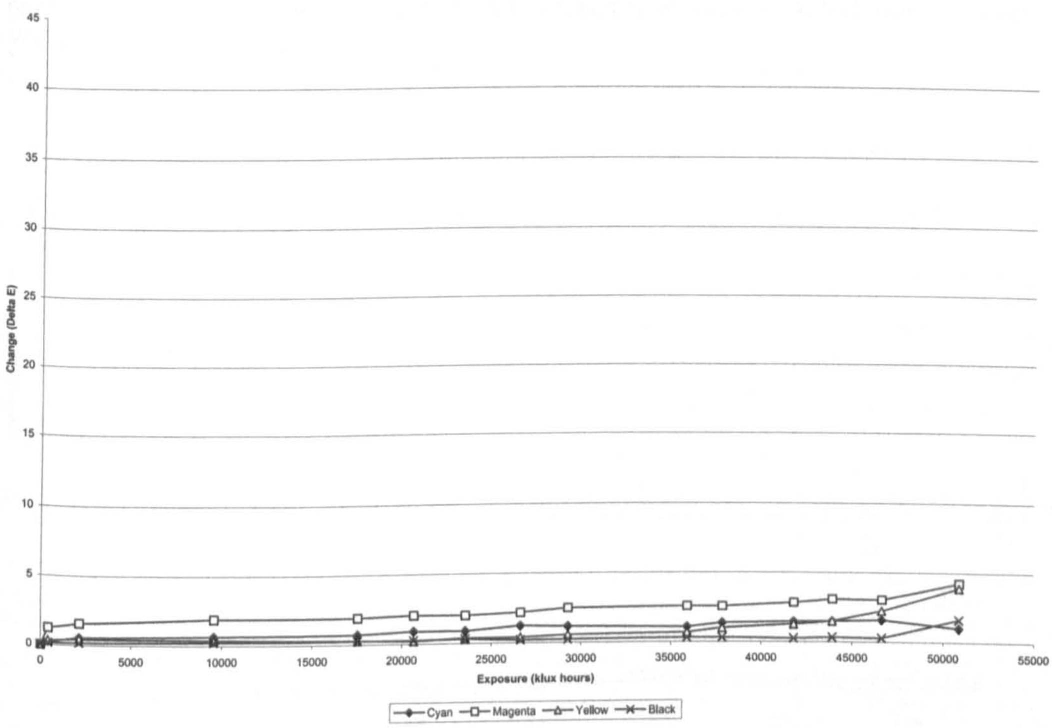
H.23 Plot showing the fading rate of the Canon CLBP 460PS samples printed on Canon Ultra White (5.4) exposed to natural daylight unfiltered.



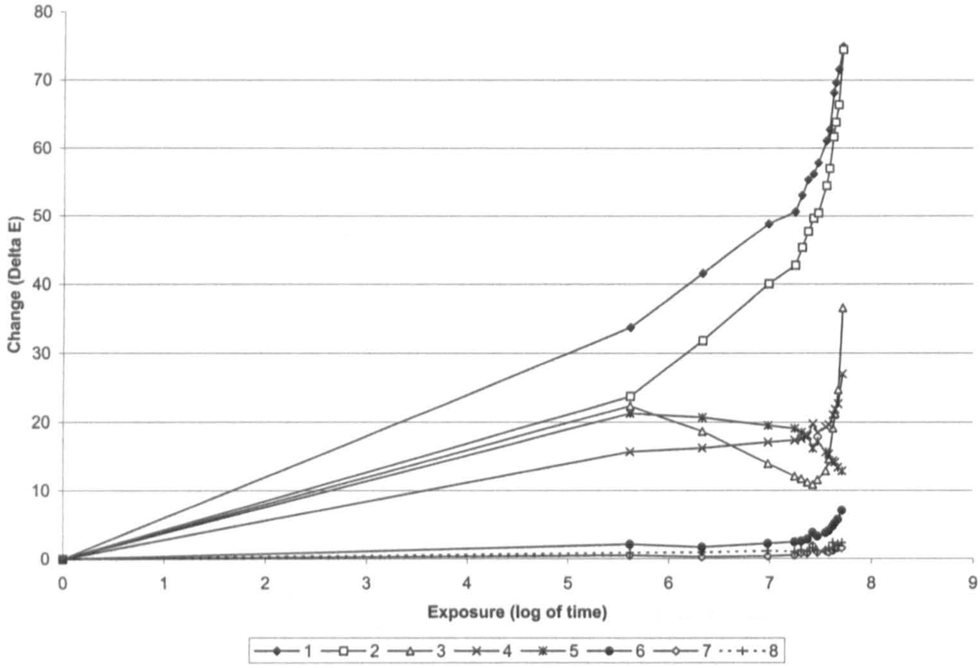
H.24 Plot showing the fading rate of the Canon CLBP 460PS samples printed on Canon Ultra White (5.4) exposed to natural daylight under an UV filter.



H.25 Plot showing the fading rate of the Canon CLBP 460PS samples printed on Canon Card (5.5) exposed to natural daylight unfiltered.

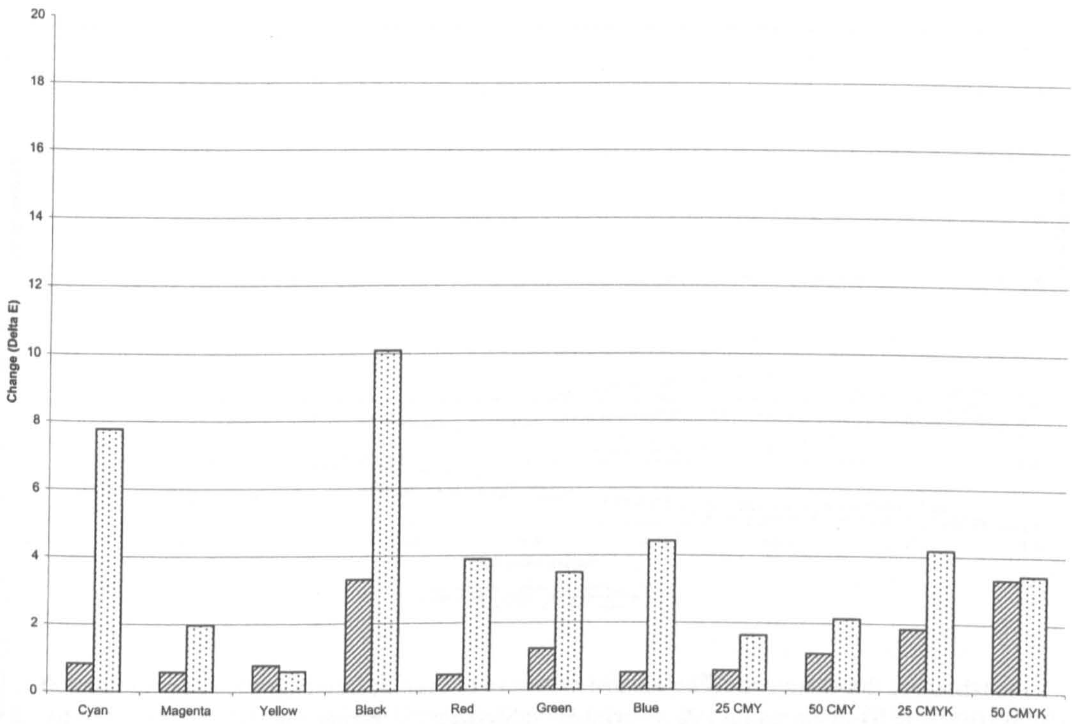


H.26 Plot showing the fading rate of the Canon CLBP 460PS samples printed on Canon Card (5.5) exposed to natural daylight under an UV filter.

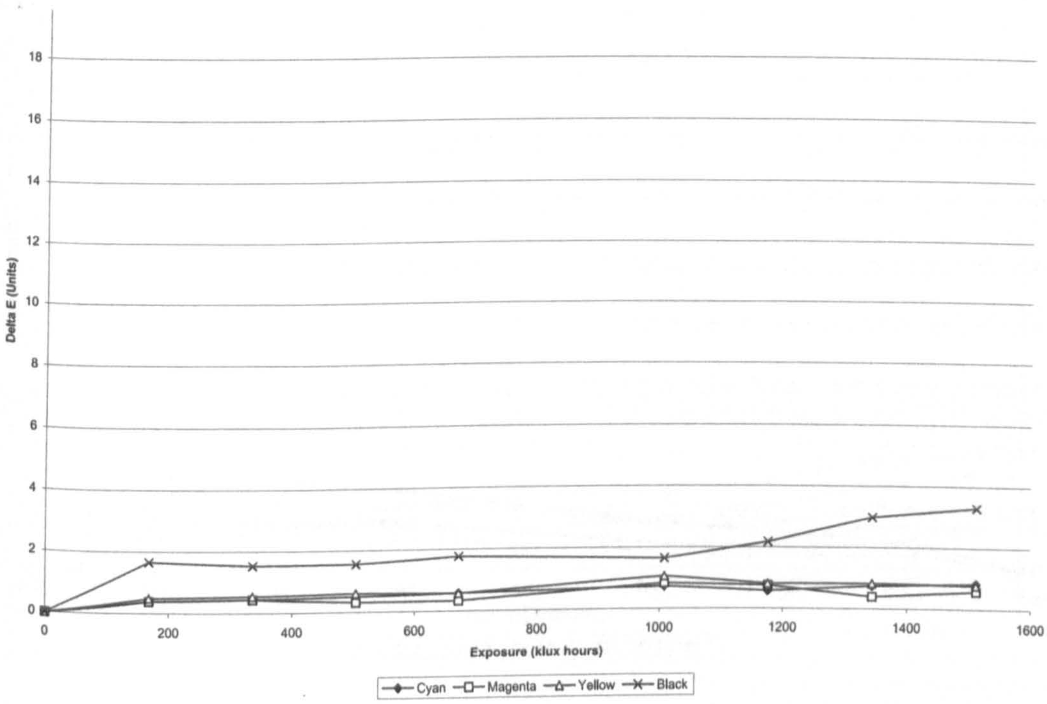


H.27 Plot of the fading rate against log of time of the blue wool scales exposed to the natural daylight ageing test without an UV filter.

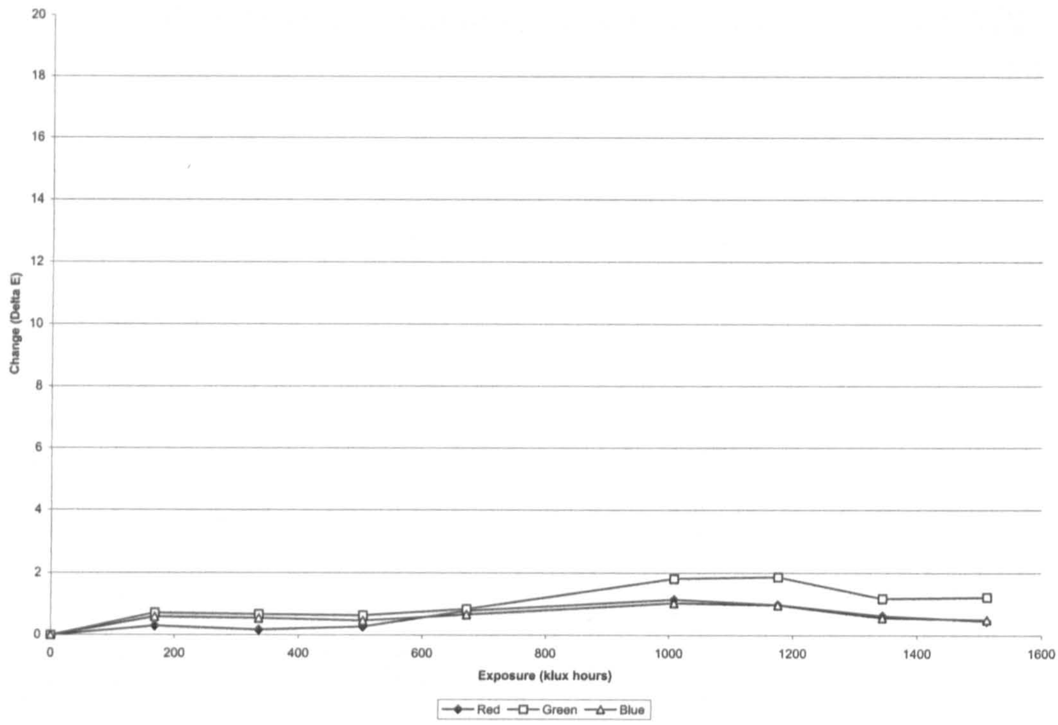
APPENDIX I - Fading rates of the samples exposed to the tungsten-halogen light fastness tester



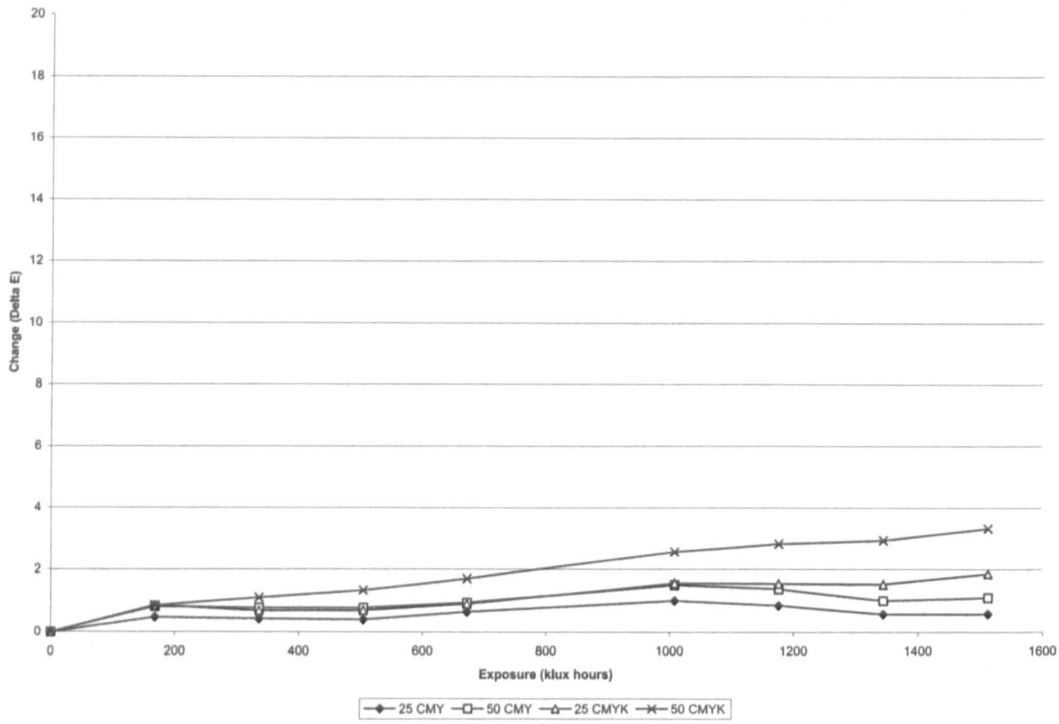
I.1 Bar chart to compare the change in ΔEab against exposure of the primary ink colours and their print combinations from the Iris Morgan FA ink set printed on Somerset Velvet paper (1.1) and Whatman watercolour paper (1.2).



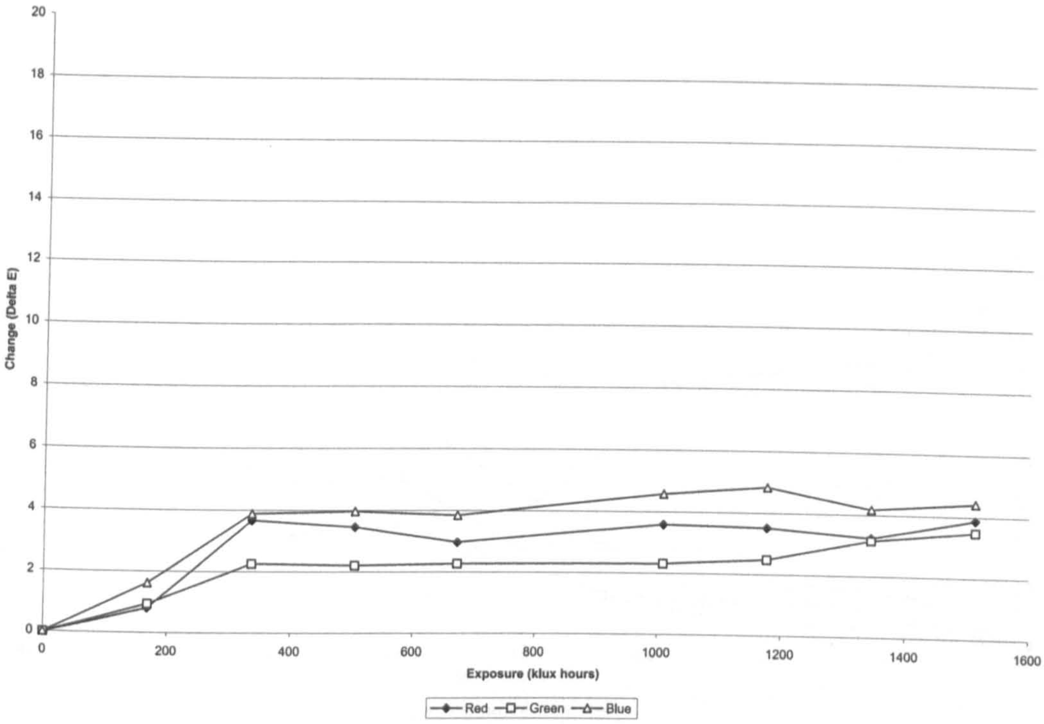
I.2 Plot showing the change in ΔEab against exposure of the CMYK inks from the Iris Morgan FA ink set printed on Somerset Velvet paper (1.1) on exposure to tungsten halogen light.



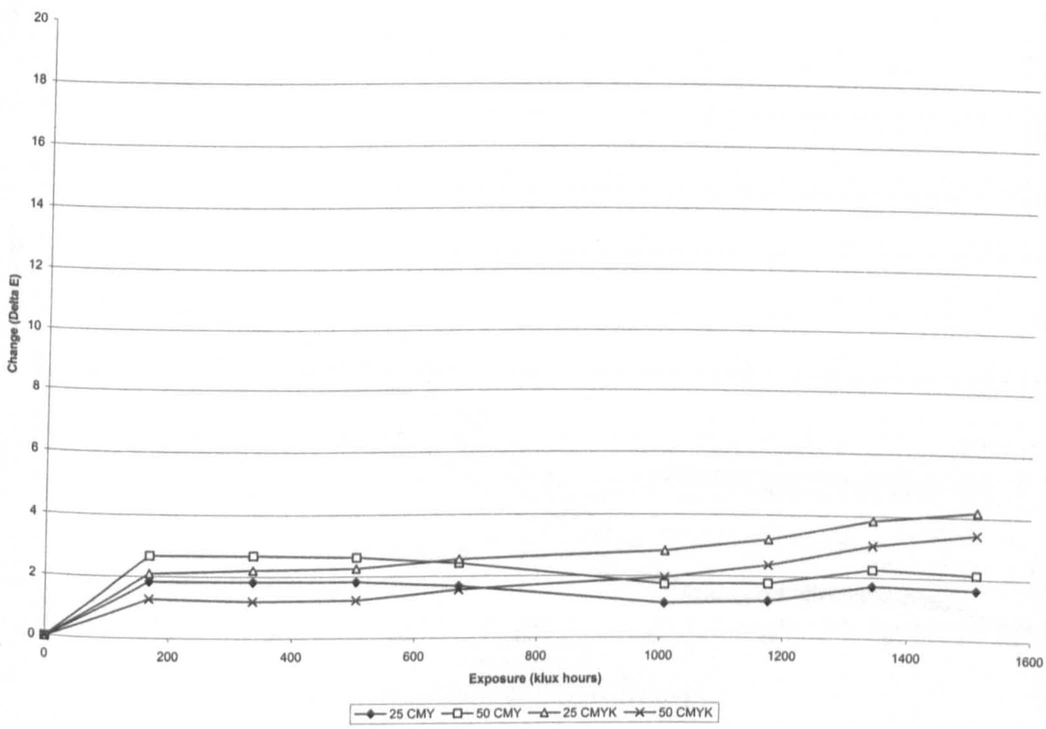
I.3 Plot showing the change in ΔEab against exposure of the CMY inks printed in combination (RGB) from the Iris Morgan FA ink set printed on Somerset Velvet paper (1.1) on exposure to tungsten halogen light.



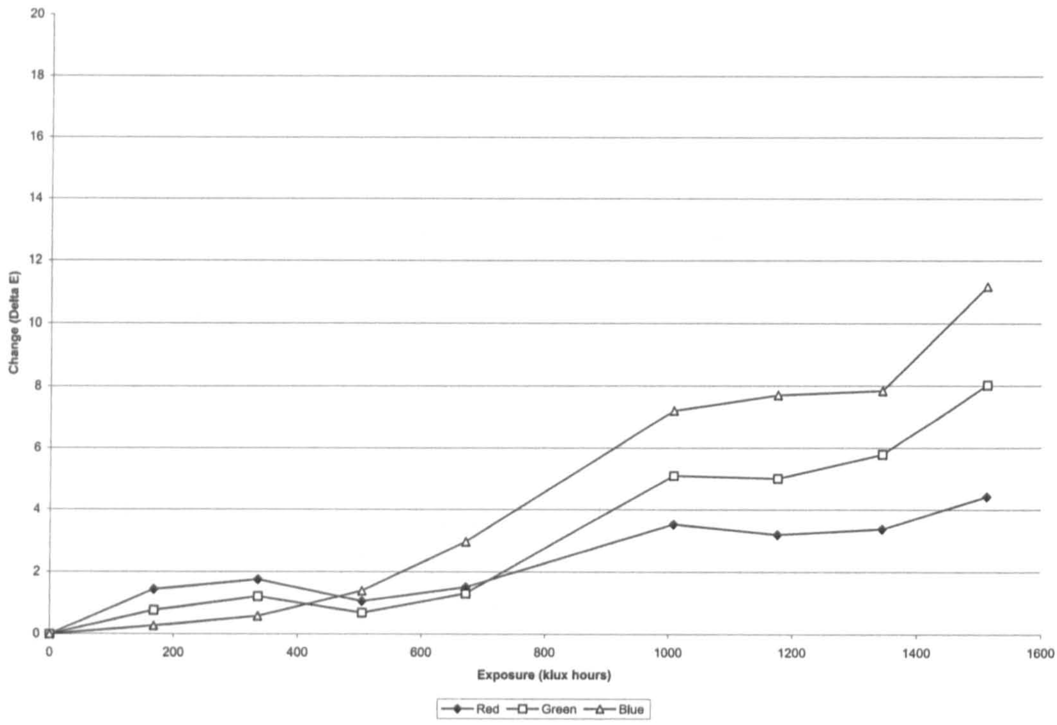
I.4 Plot showing the change in ΔEab against exposure of the CMY inks printed with 50 % K from the Iris Morgan FA ink set printed on Somerset Velvet paper (1.1) on exposure to tungsten halogen light.



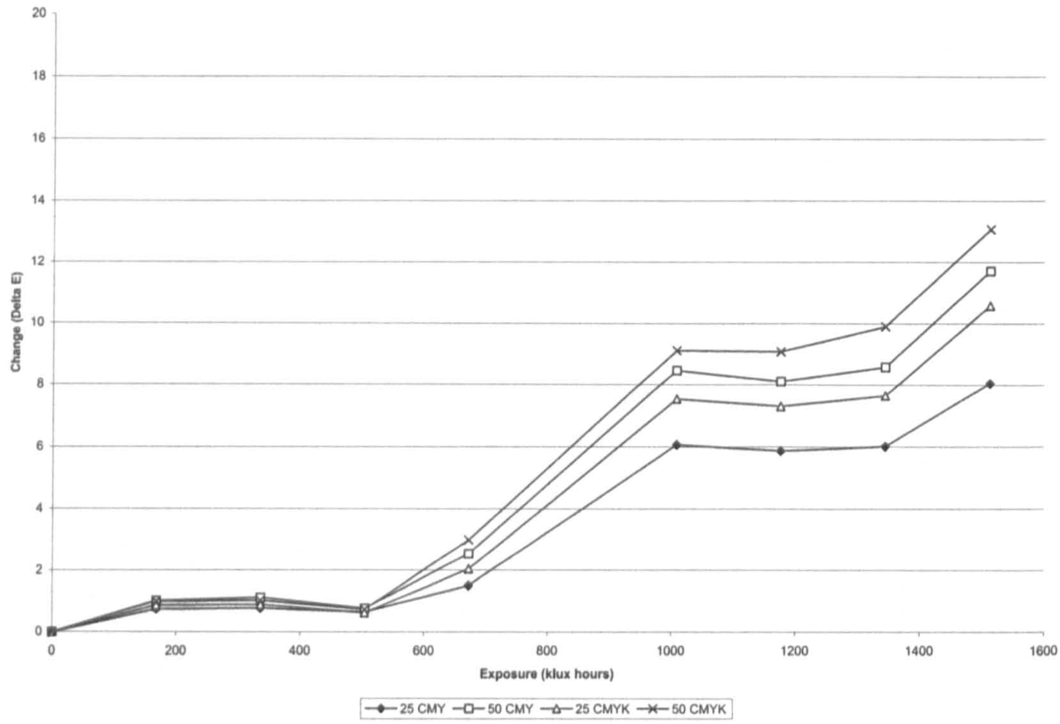
I.5 Plot showing the change in ΔEab against exposure of the CMY inks printed in combination (RGB) from the Iris Morgan FA ink set printed on Whatman watercolour paper (1.2) on exposure to tungsten halogen light.



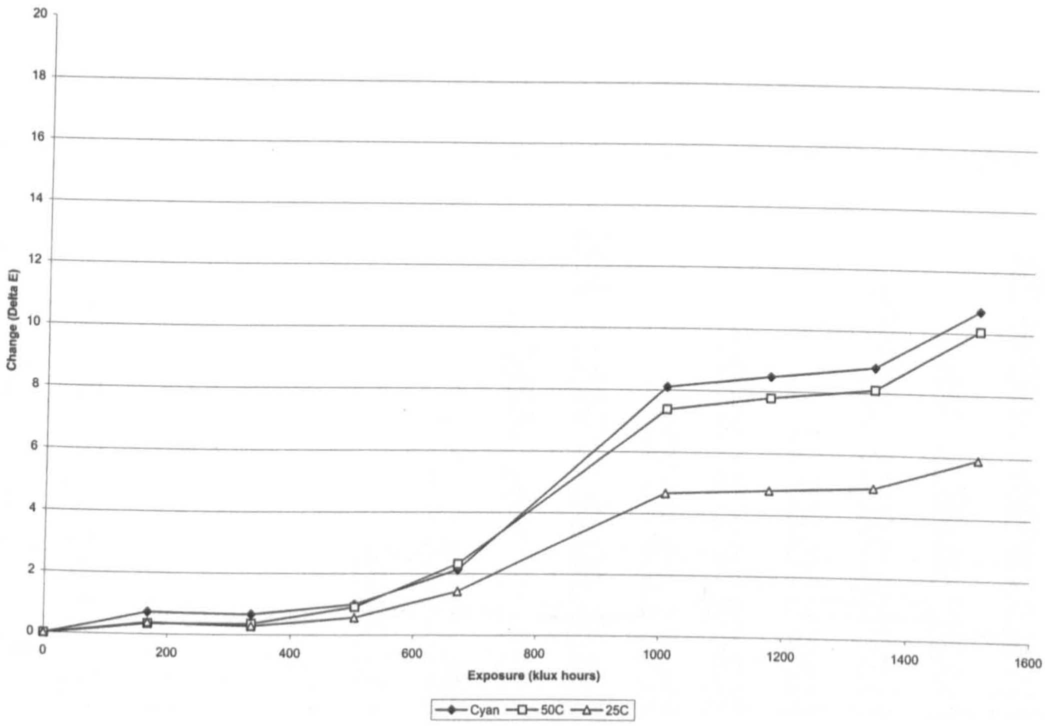
I.6 Plot showing the change in ΔEab against exposure of the CMY inks printed with 50 % K from the Iris Morgan FA ink set printed on Whatman watercolour paper (1.2) on exposure to tungsten halogen light.



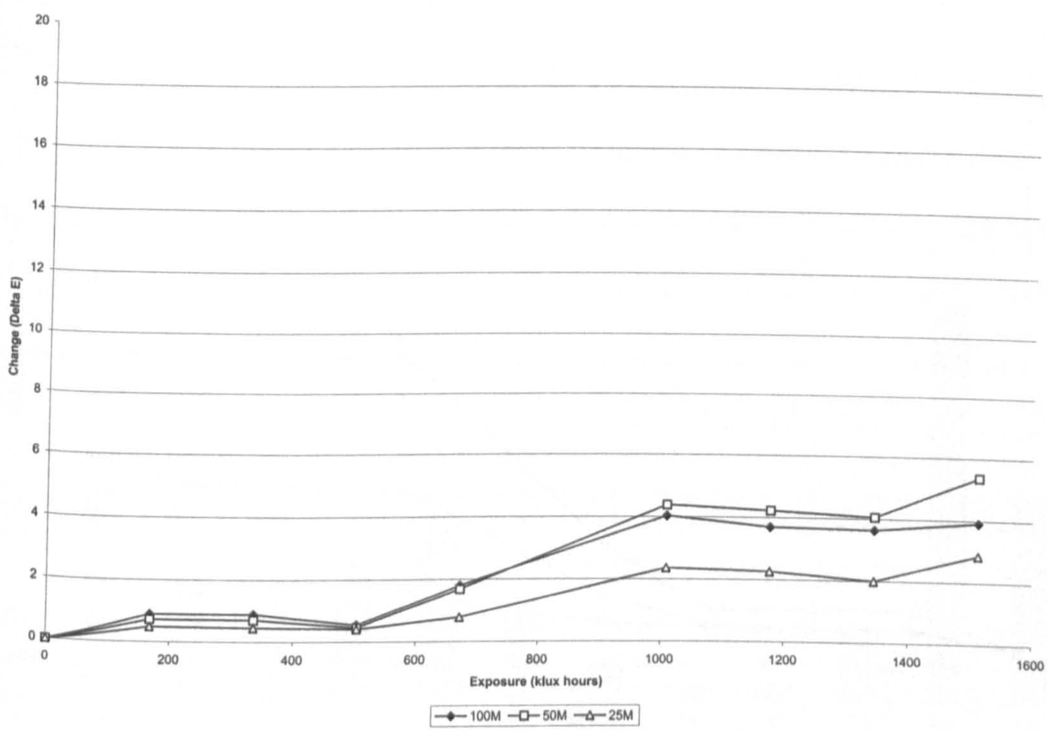
I.7 Plot showing the change in ΔEab against exposure of the CMY inks printed in combination (RGB) from the Epson Pro 9000 ink set printed on Epson Photo Glossy paper (3.1) on exposure to tungsten halogen light.



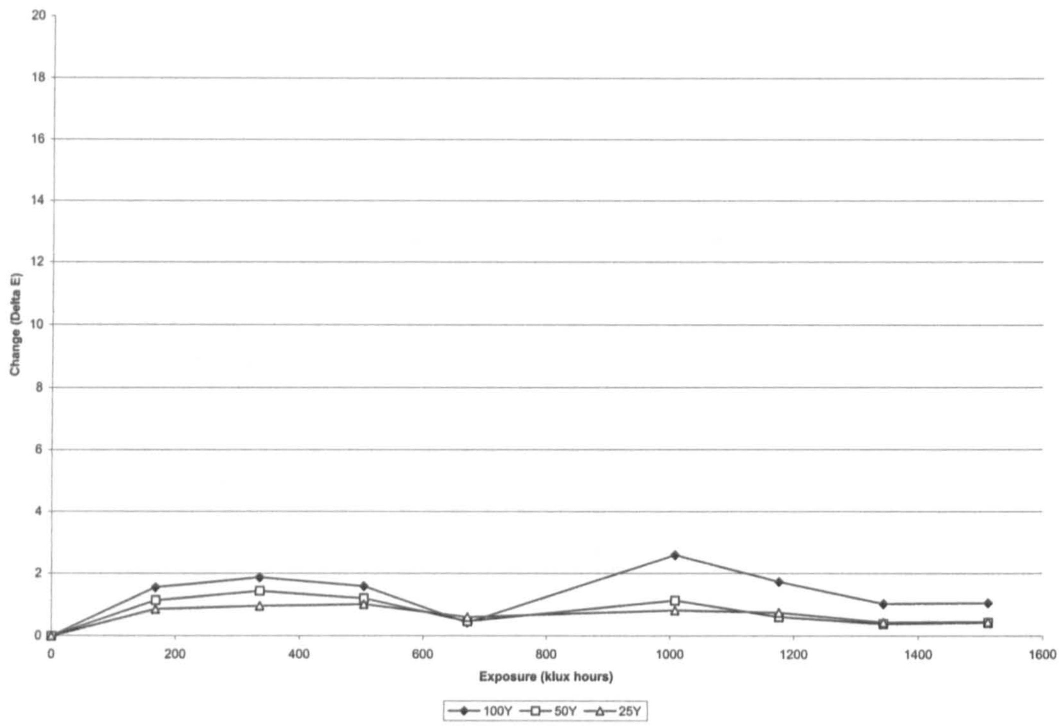
I.8 Plot showing the change in ΔEab against exposure of the CMYK inks printed in combination from the Epson Pro 9000 ink set printed on Epson Photo Glossy paper (3.1) on exposure to tungsten halogen light.



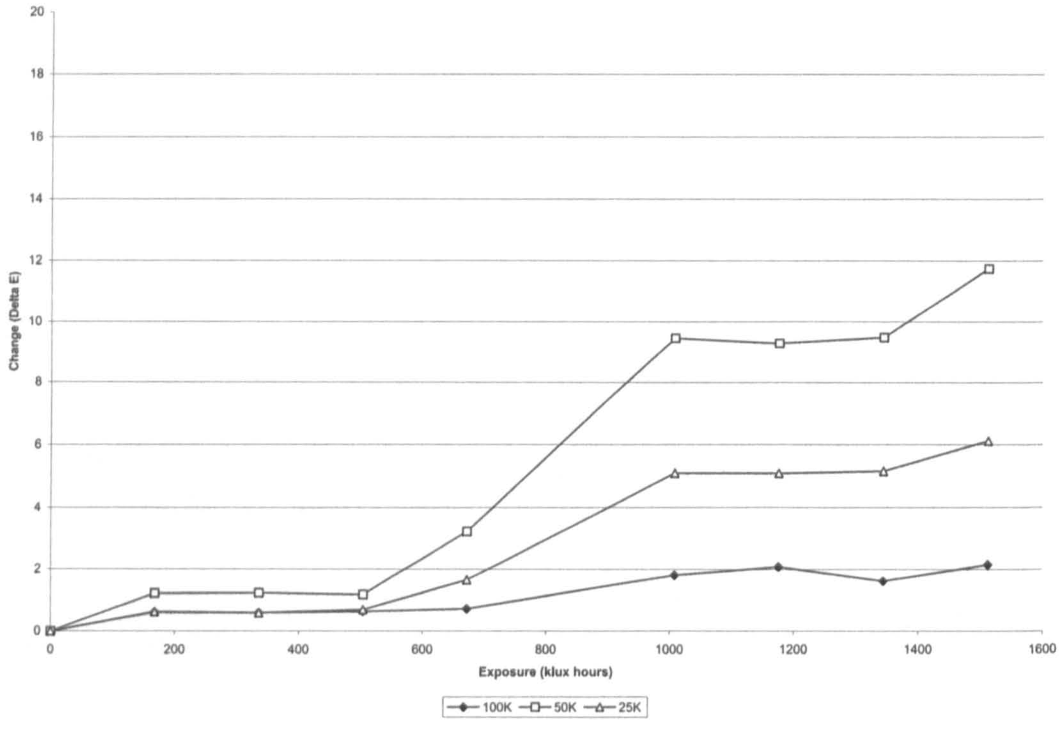
I.9 Plot showing the change in ΔEab against exposure of the cyan ink printed in different concentrations from the Epson Pro 9000 ink set printed on Epson Photo Glossy paper (3.1) on exposure to tungsten halogen light.



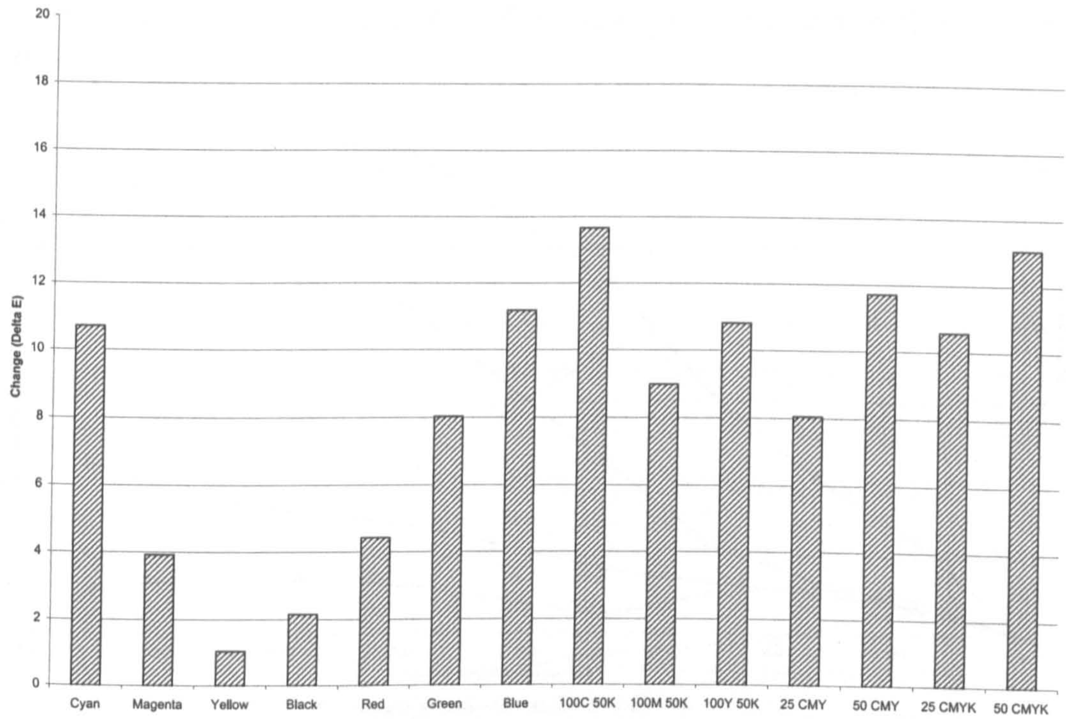
I.10 Plot showing the change in ΔEab against exposure of the magenta ink printed in different concentrations from the Epson Pro 9000 ink set printed on Epson Photo Glossy paper (3.1) on exposure to tungsten halogen light.



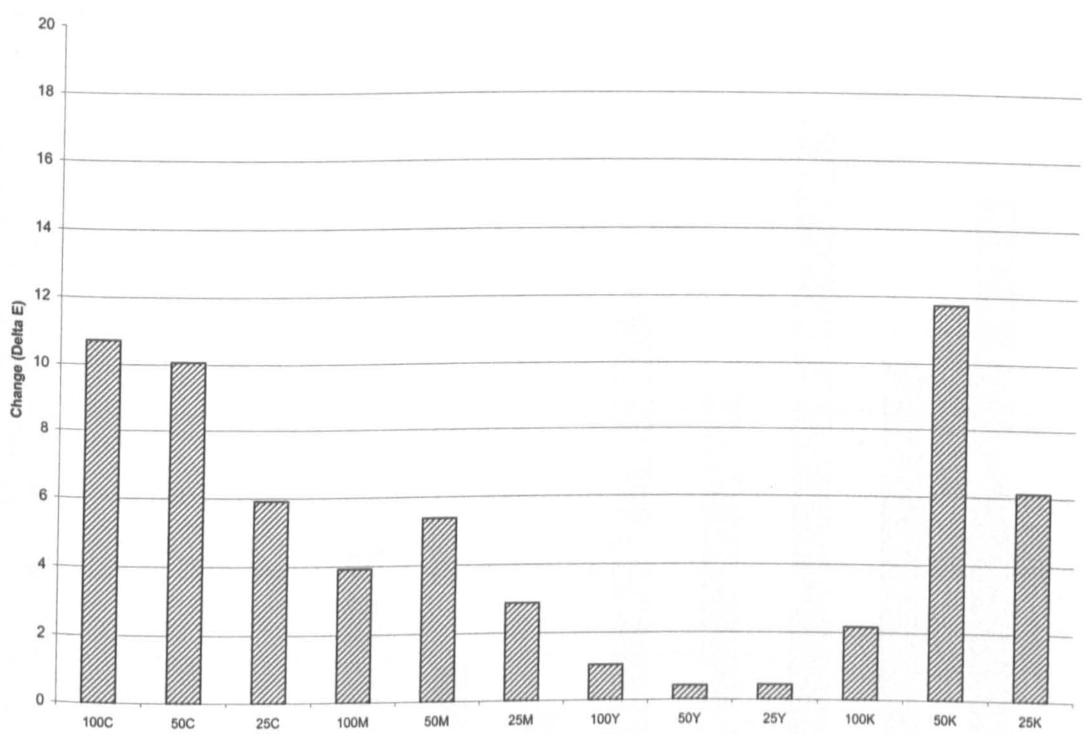
I.11 Plot showing the change in ΔEab against exposure of the yellow ink printed in different concentrations from the Epson Pro 9000 ink set printed on Epson Photo Glossy paper (3.1) on exposure to tungsten halogen light.



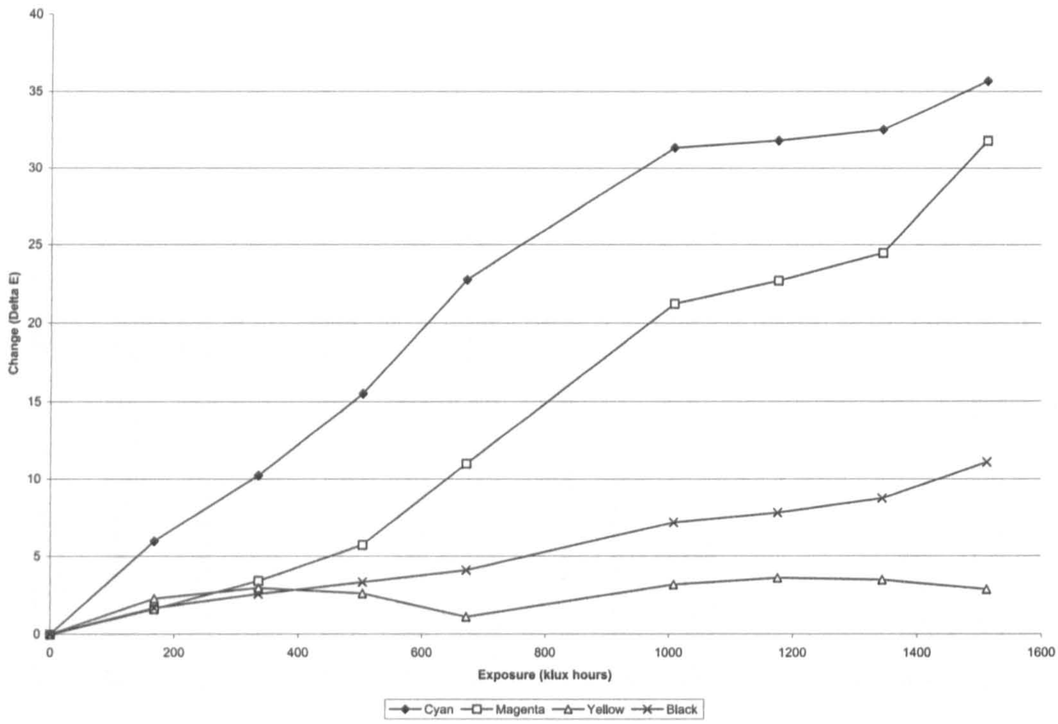
I.12 Plot showing the change in ΔEab against exposure of the black ink printed in different concentrations from the Epson Pro 9000 ink set printed on Epson Photo Glossy paper (3.1) on exposure to tungsten halogen light.



I.13 Bar chart showing the change in ΔEab against exposure of the primary ink colours and their print combinations from the Epson Pro 9000 ink set printed on Epson Photo Glossy paper (3.1).

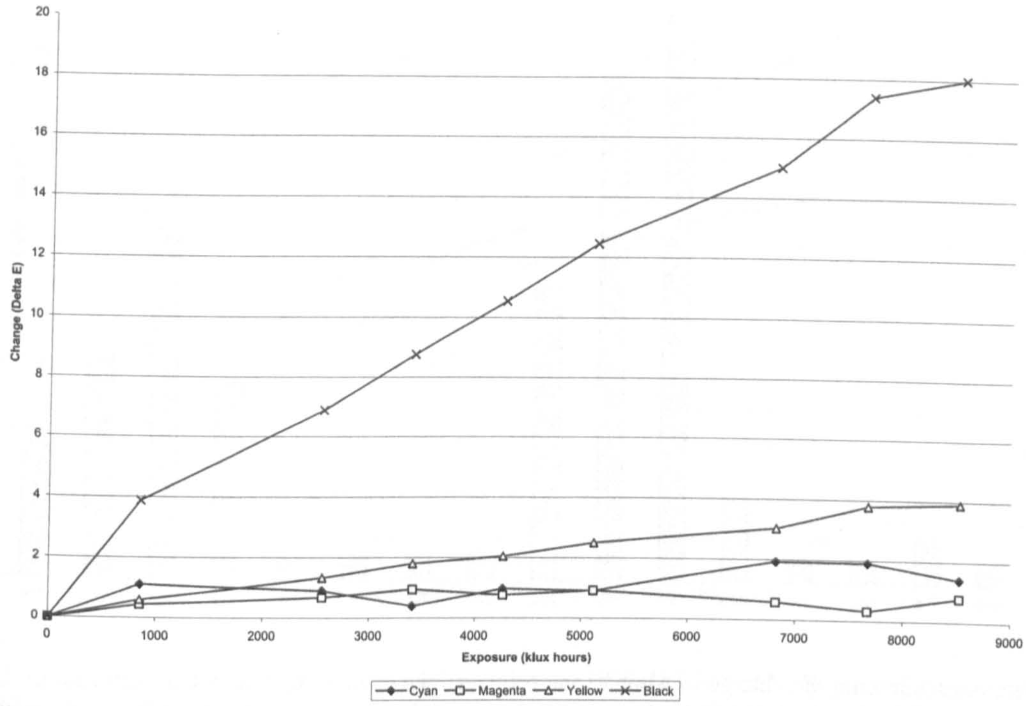


I.14 Bar chart showing the change in ΔEab against exposure of the primary ink colours printed in different concentrations from the Epson Pro 9000 ink set printed on Epson Photo Glossy paper (3.1).

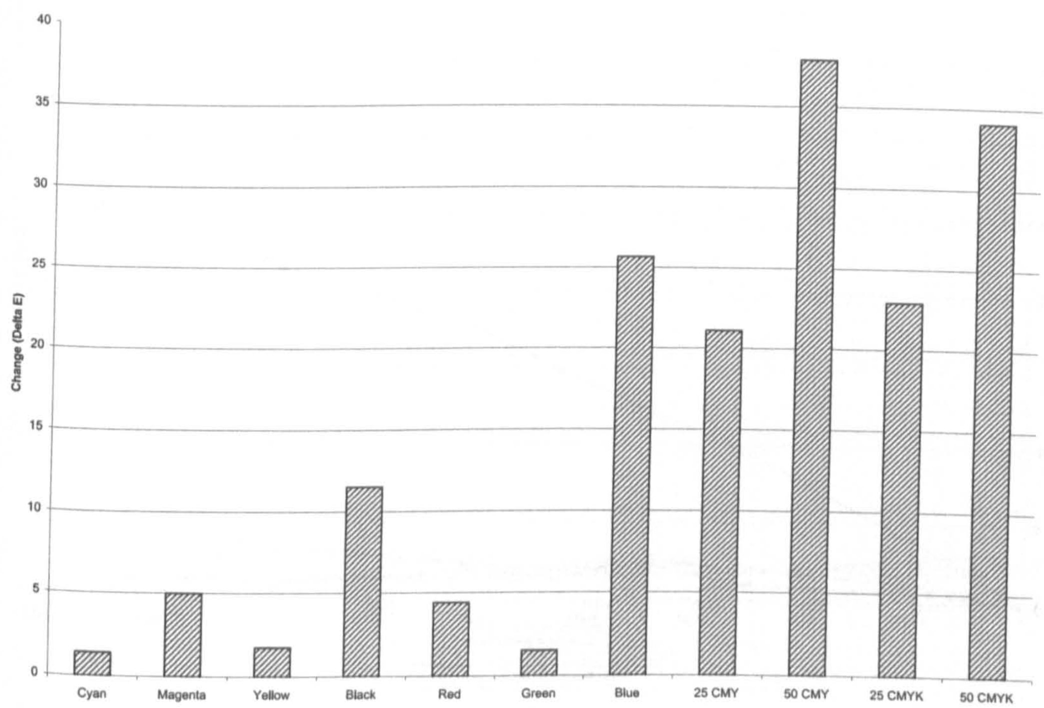


I.15 Plot showing the change in ΔEab against exposure of the CMYK inks printed in combination from the Epson Pro 9000 ink set printed on ISVE paper (3.2) on exposure to tungsten halogen light.

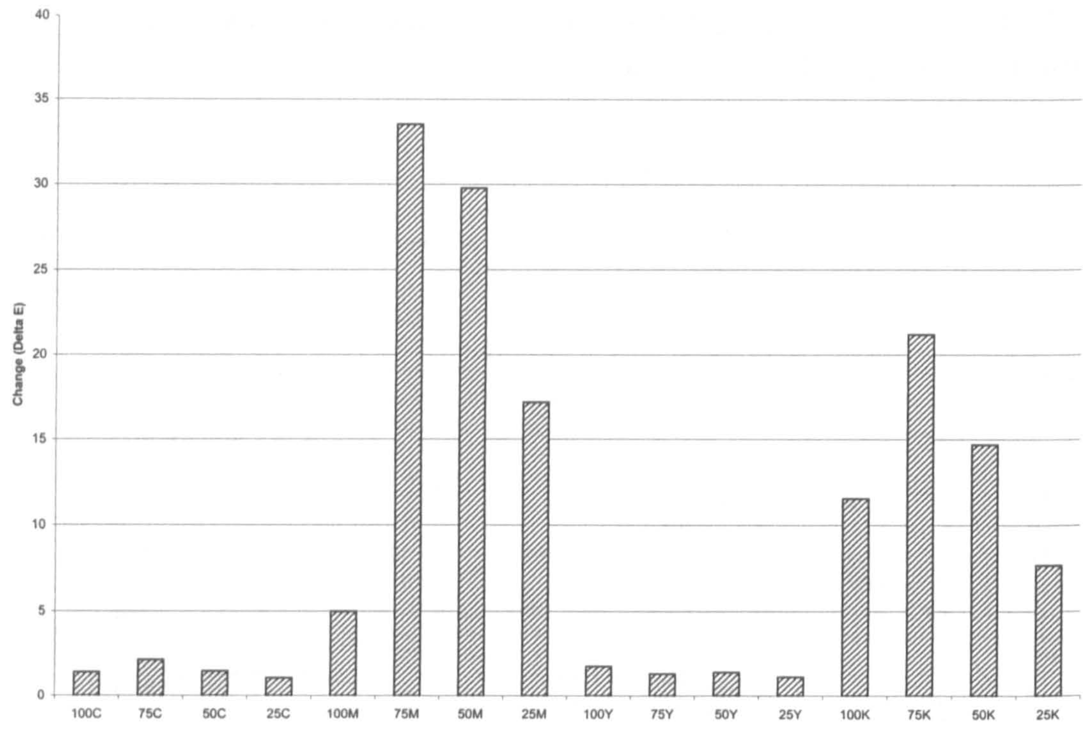
APPENDIX J - Fading rates of the samples exposed to the fluorescent light fastness tester



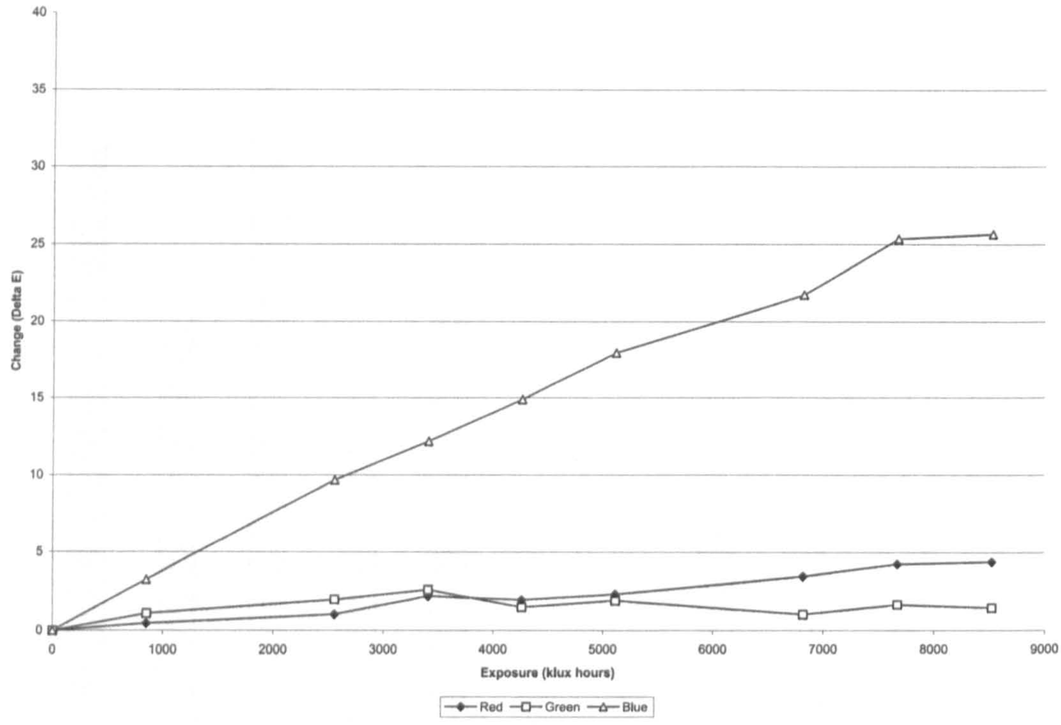
J.1 Plot showing the change in ΔEab against exposure of the CMYK inks from the Iris Morgan FA ink set printed on Whatman watercolour paper (1.2) exposed to the fluorescent light fastness test under an UV filter.



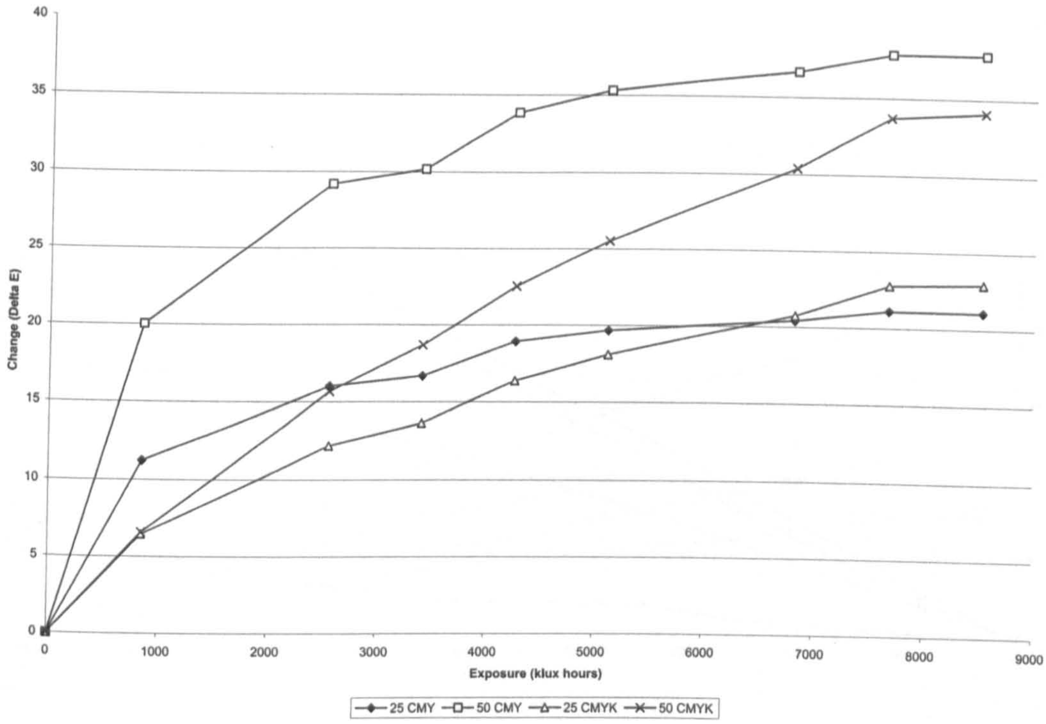
J.2 Bar chart showing the change in ΔEab of the primary inks and their combinations Epson Pro 9000 ink set printed on ISVE paper (3.2) exposed to the fluorescent light fastness tester under an UV filter.



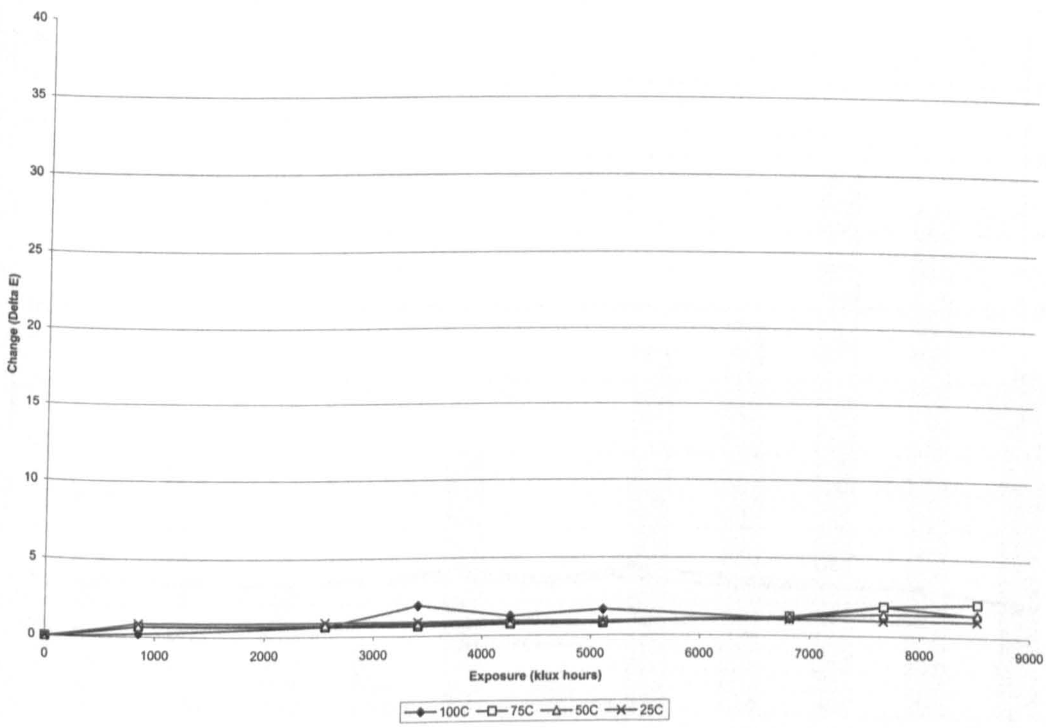
J.3 Bar chart showing the change in ΔEab of the primary inks printed in different concentrations Epson Pro 9000 ink set printed on ISVE paper (3.2) exposed to the fluorescent light fastness tester under an UV filter.



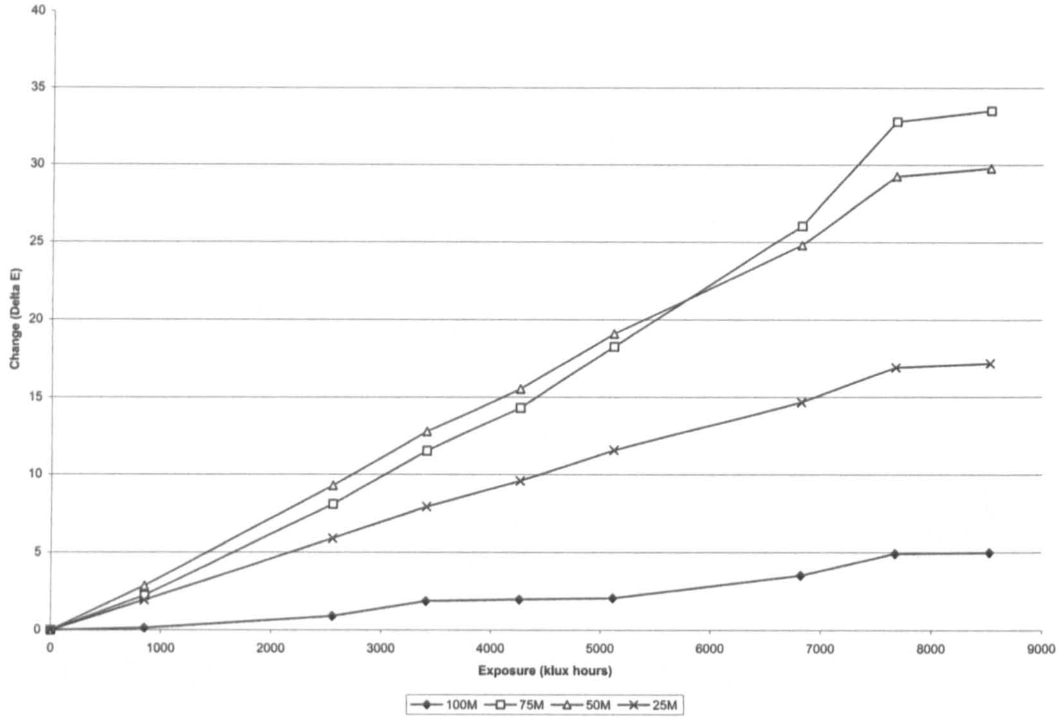
J.4 Plot showing the change in ΔEab against exposure of the RGB ink patches from the Epson Pro 9000 ink set printed on ISVE paper (3.2) exposed to the fluorescent light fastness tester under an UV filter.



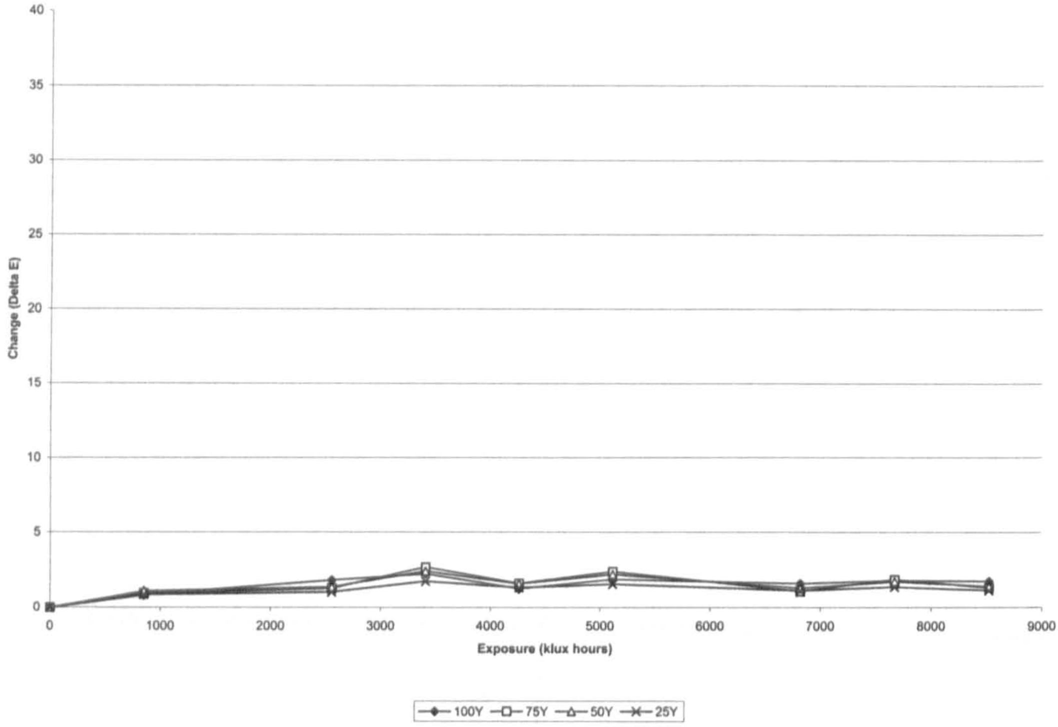
J.5 Plot showing the change in ΔEab against exposure of the 25 % and 50 % printed grey scales from the Epson Pro 9000 ink set produced on the ISVE paper (3.2) exposed to the light fastness tester under an UV filter.



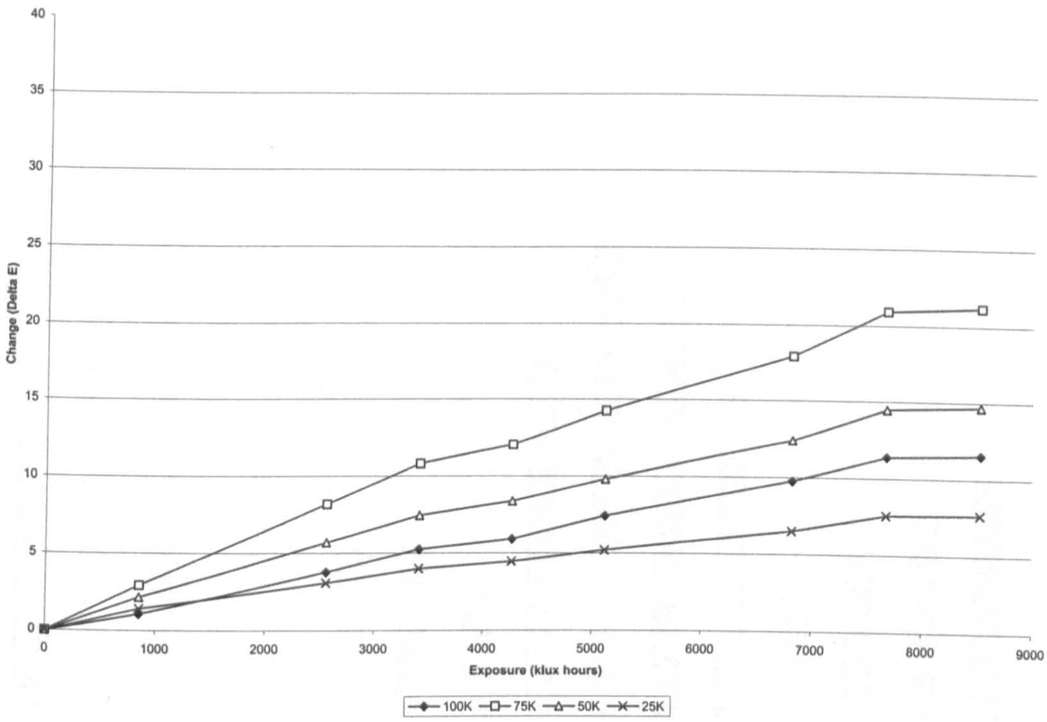
J.6 Plot showing the change in ΔEab against exposure of the cyan ink from the Epson Pro 9000 ink set printed in different concentrations on ISVE paper (3.2) exposed to the fluorescent light fastness tester under an UV filter.



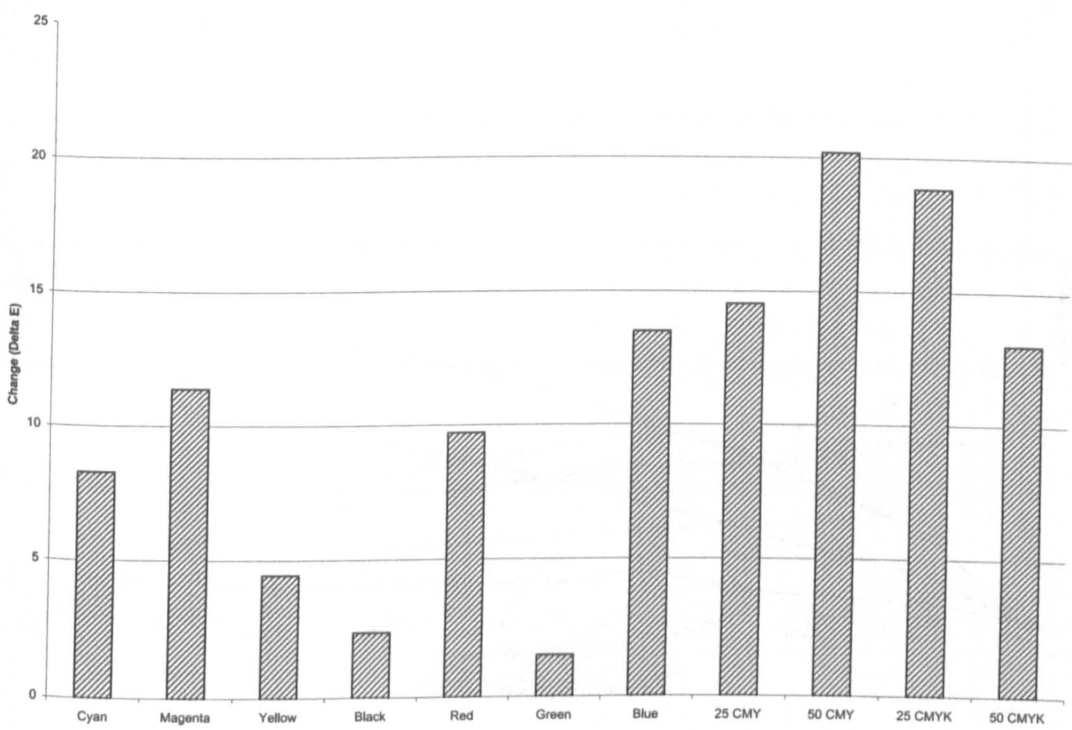
J.7 Plot showing the change in ΔEab against exposure of the magenta ink from the Epson Pro 9000 ink set printed at different concentrations on ISVE paper (3.2) exposed to the fluorescent light fastness tester under an UV filter.



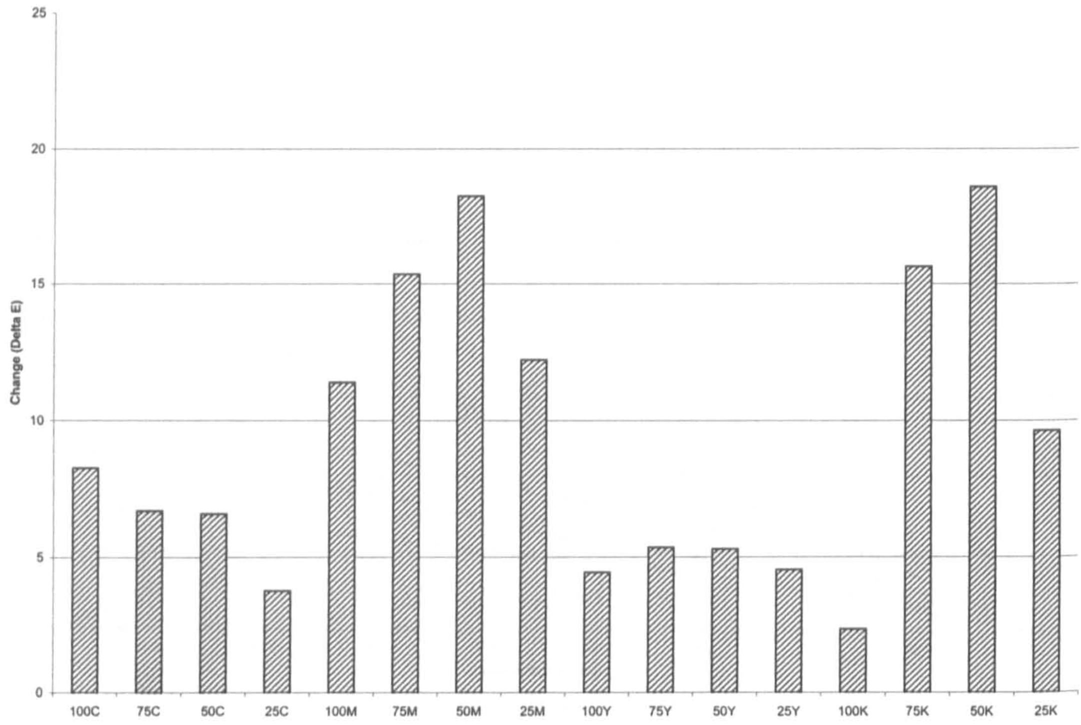
J.8 Plot showing the change in ΔEab against exposure of the yellow ink from the Epson Pro 9000 ink set printed at different concentrations on ISVE paper (3.2) exposed to the fluorescent light fastness tester under an UV filter.



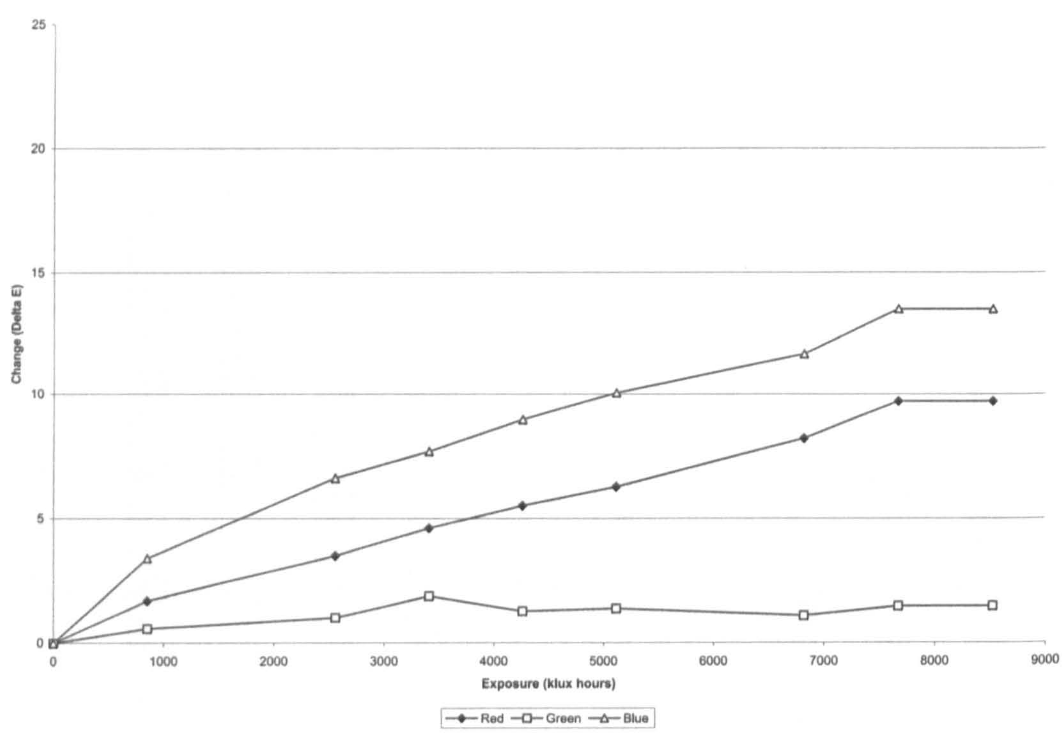
J.9 Plot showing the change in ΔEab against exposure of the black ink from the Epson Pro 9000 ink set printed in different concentrations on ISVE paper (3.2) exposed to the fluorescent light fastness tester under an UV filter.



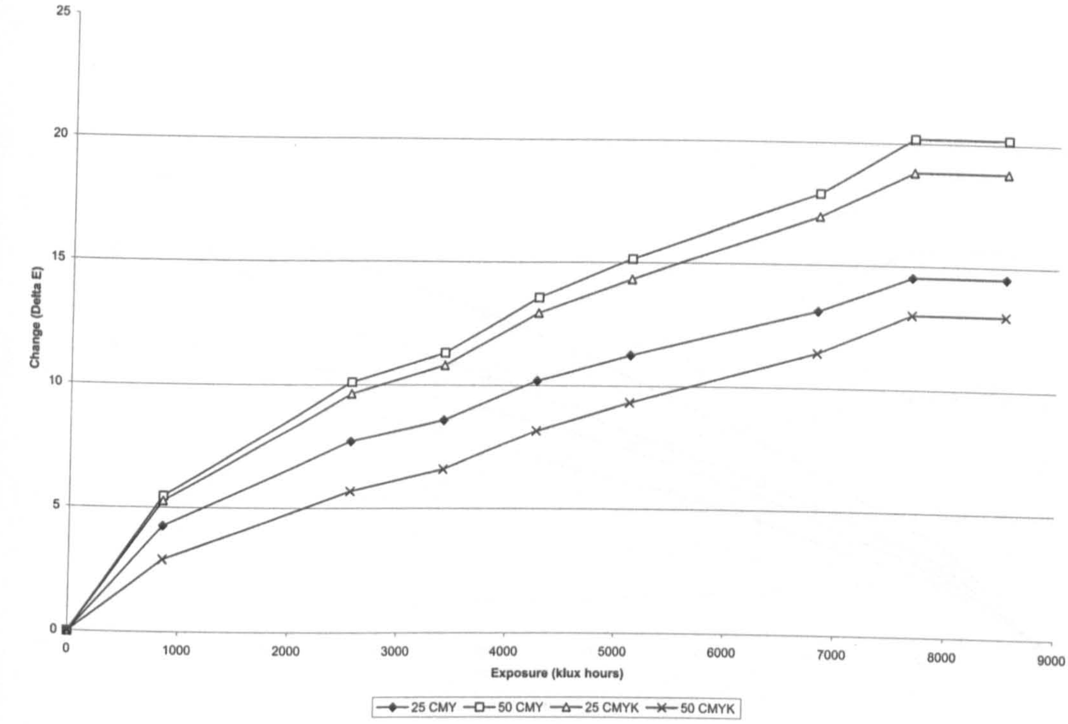
J.10 Bar chart showing the change in ΔEab of the primary inks and their combinations Epson Pro 9000 ink set printed on Somerset Velvet paper (3.3) exposed to the fluorescent light fastness tester under an UV filter.



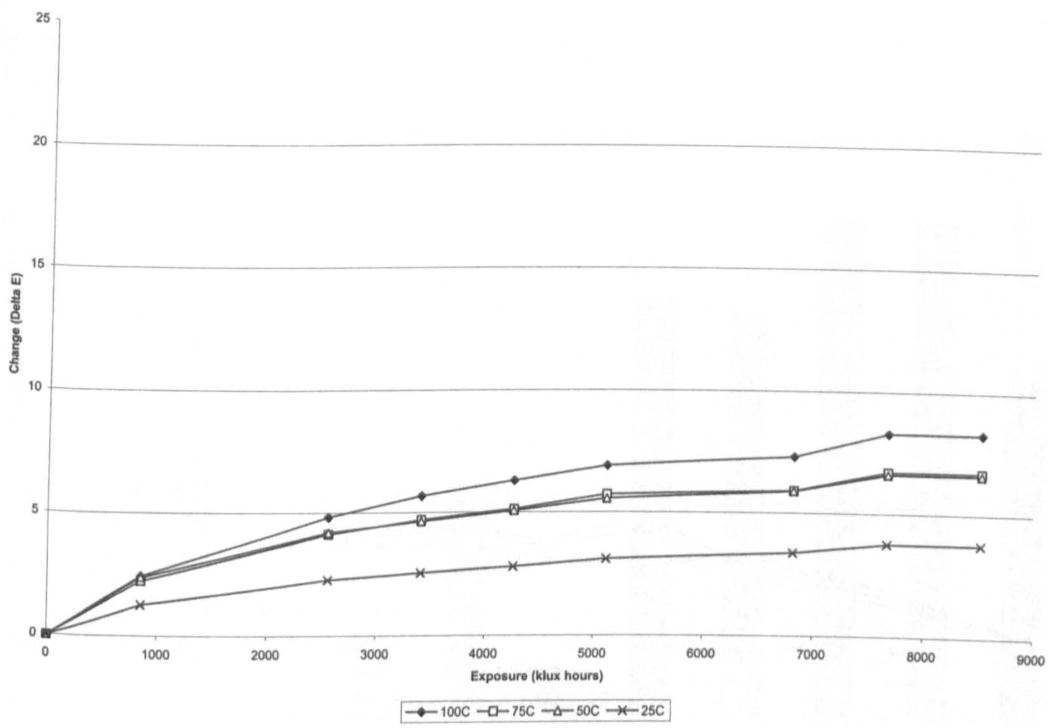
J.11 Bar chart showing the change in ΔEab of the primary inks printed in different concentrations Epson Pro 9000 ink set printed on Somerset Velvet paper (3.3) exposed to the fluorescent light fastness tester under an UV filter.



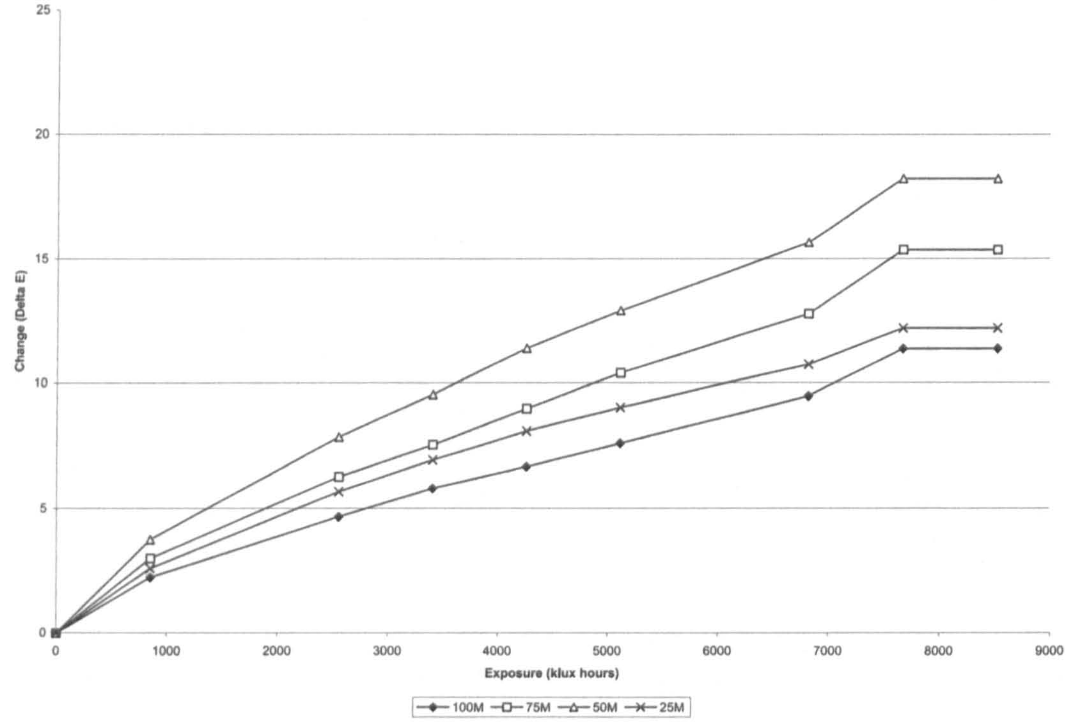
J.12 Plot showing the change in ΔEab against exposure of the RGB ink patches from the Epson Pro 9000 ink set printed on Somerset Velvet paper (3.3) exposed to the fluorescent light fastness tester under an UV filter.



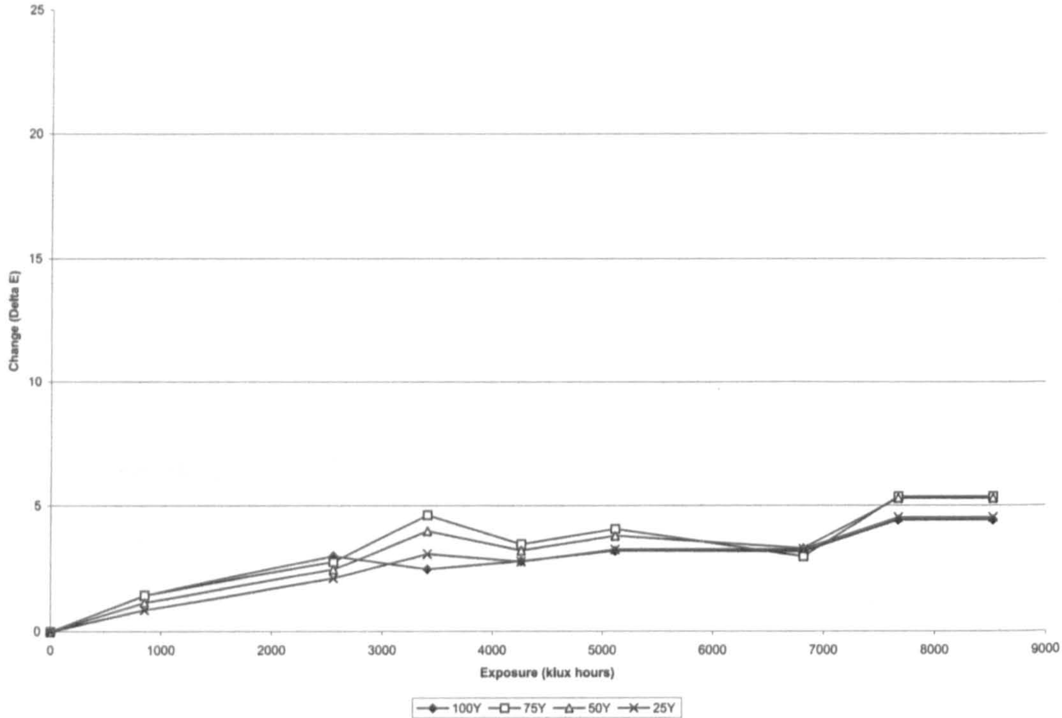
J.13 Plot showing the change in ΔEab against exposure of the 25 % and 50 % printed grey scales from the Epson Pro 9000 ink set produced on the Somerset Velvet paper (3.3) exposed to the lightfastness tester under an UV filter.



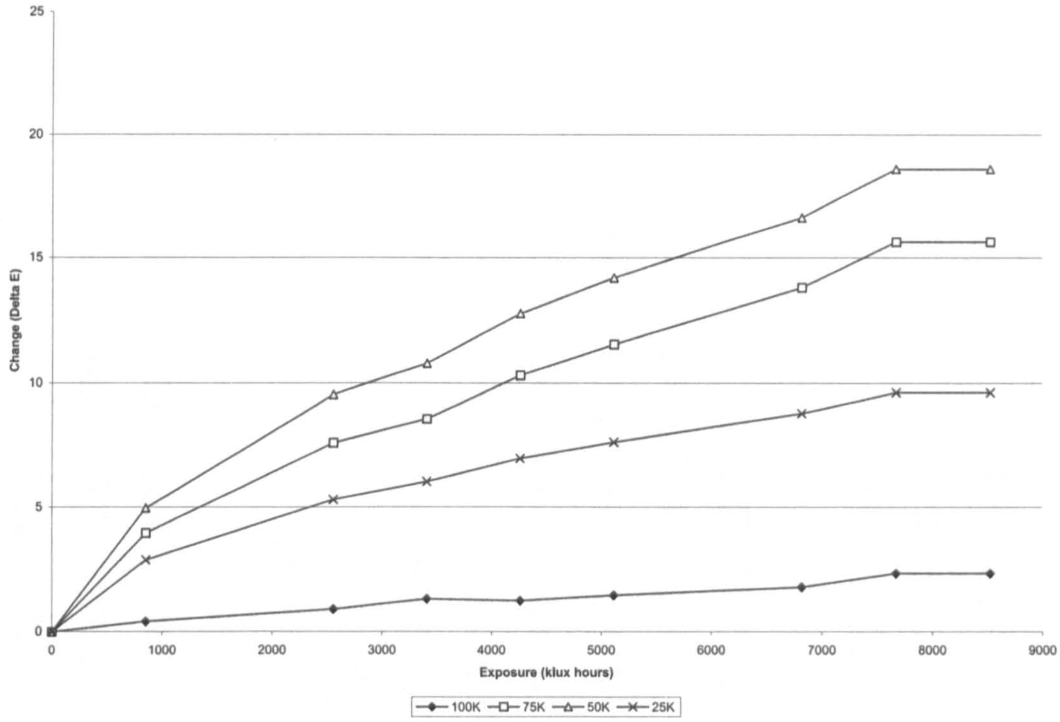
J.14 Plot showing the change in ΔEab against exposure of the cyan ink from the Epson Pro 9000 ink set printed in different concentrations on Somerset Velvet paper (3.3) exposed to the fluorescent light fastness tester under an UV filter.



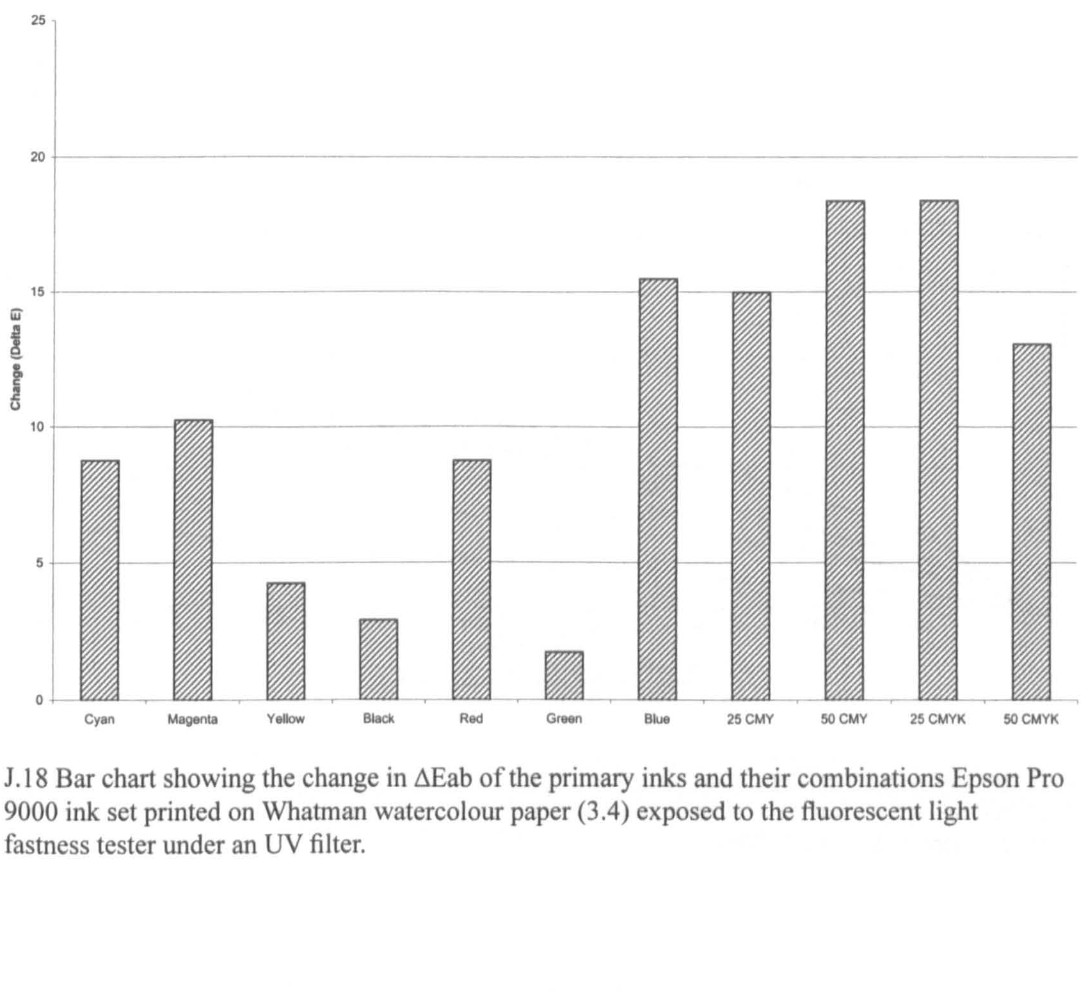
J.15 Plot showing the change in ΔEab against exposure of the magenta ink from the Epson Pro 9000 ink set printed at different concentrations on Somerset Velvet paper (3.3) exposed to the fluorescent light fastness tester under an UV filter.



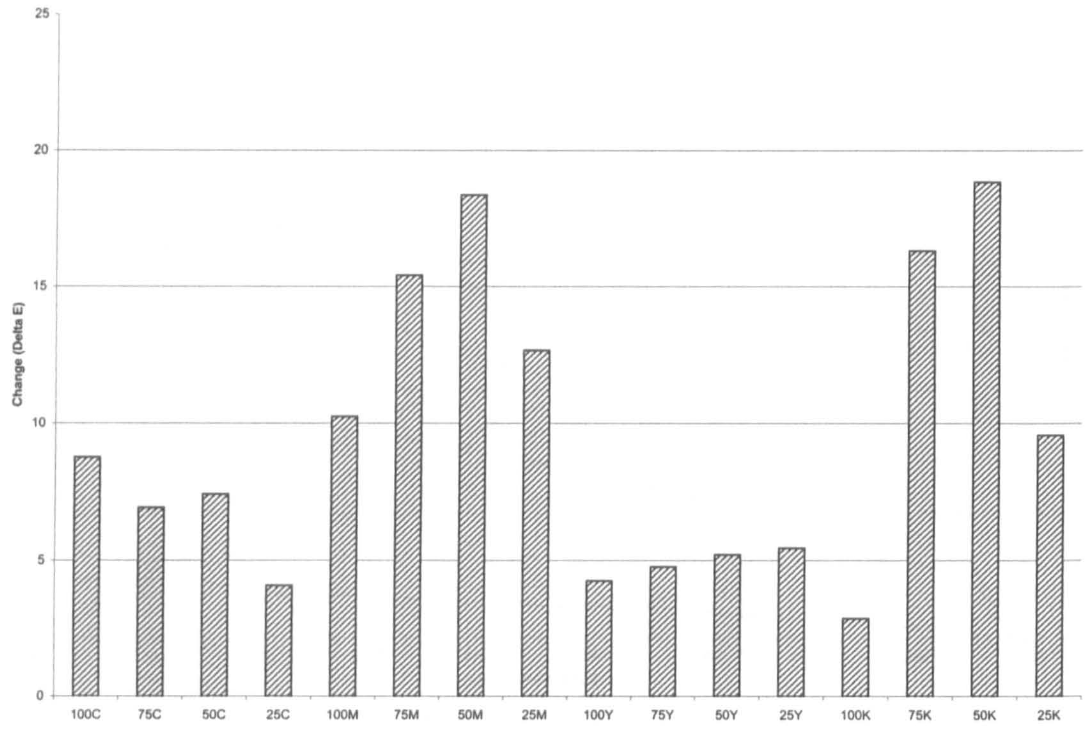
J.16 Plot showing the change in ΔEab against exposure of the yellow ink from the Epson Pro 9000 ink set printed at different concentrations on Somerset Velvet paper (3.3) exposed to the fluorescent light fastness tester under an UV filter.



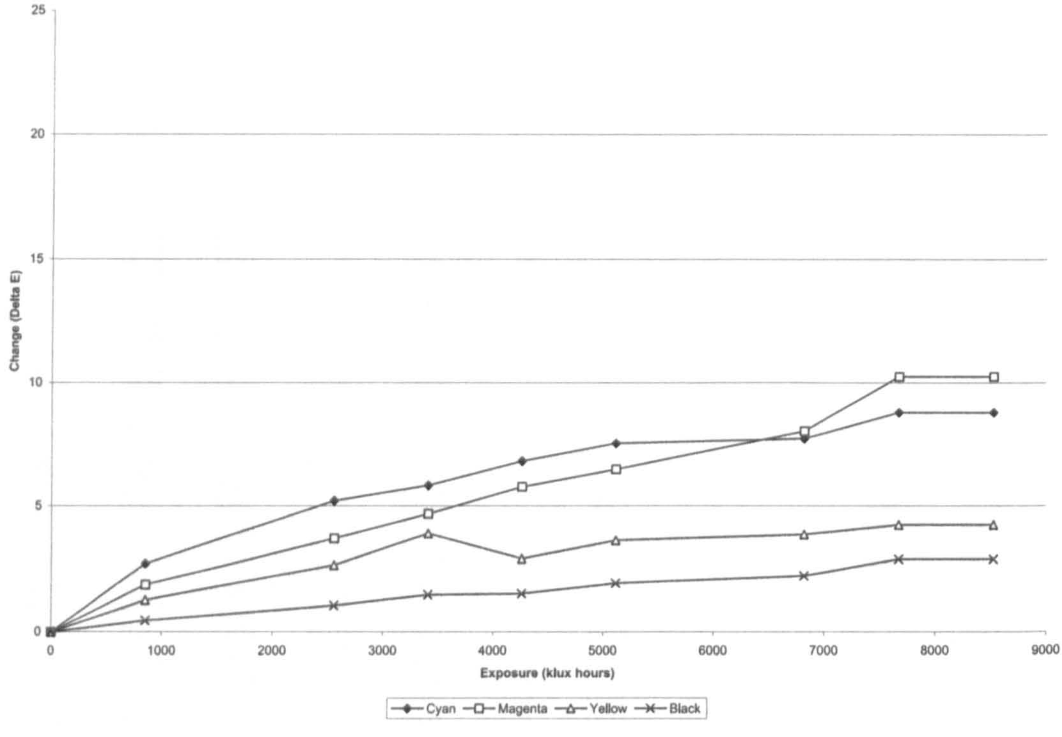
J.17 Plot showing the change in ΔEab against exposure of the black ink from the Epson Pro 9000 ink set printed in different concentrations on Somerset Velvet paper (3.3) exposed to the fluorescent light fastness tester under an UV filter.



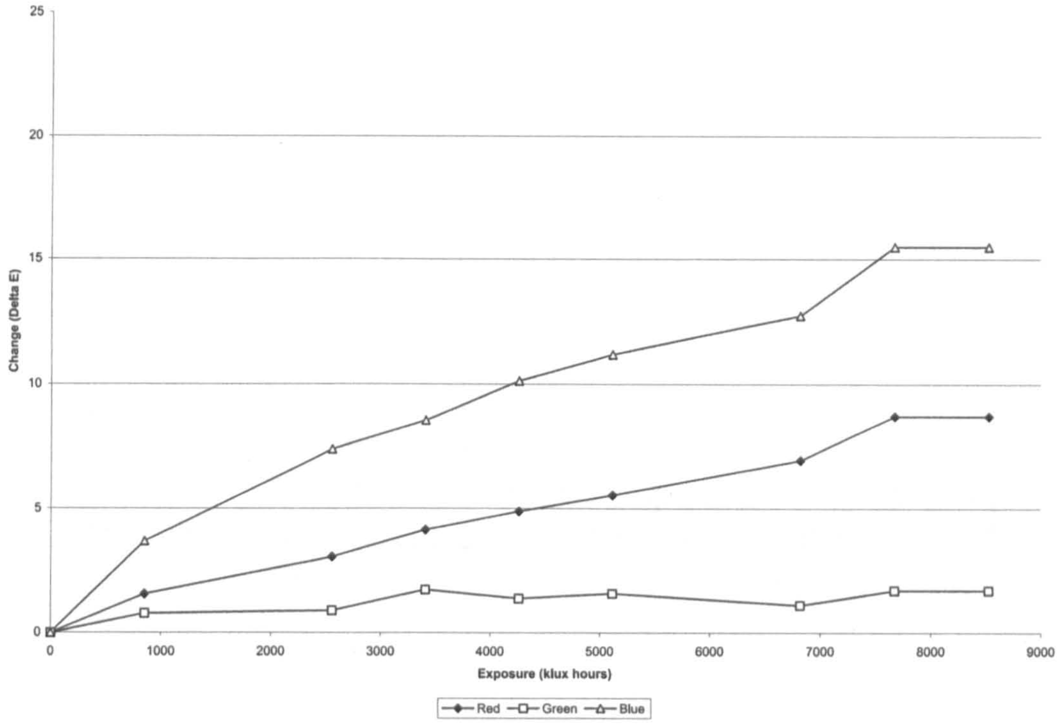
J.18 Bar chart showing the change in ΔEab of the primary inks and their combinations Epson Pro 9000 ink set printed on Whatman watercolour paper (3.4) exposed to the fluorescent light fastness tester under an UV filter.



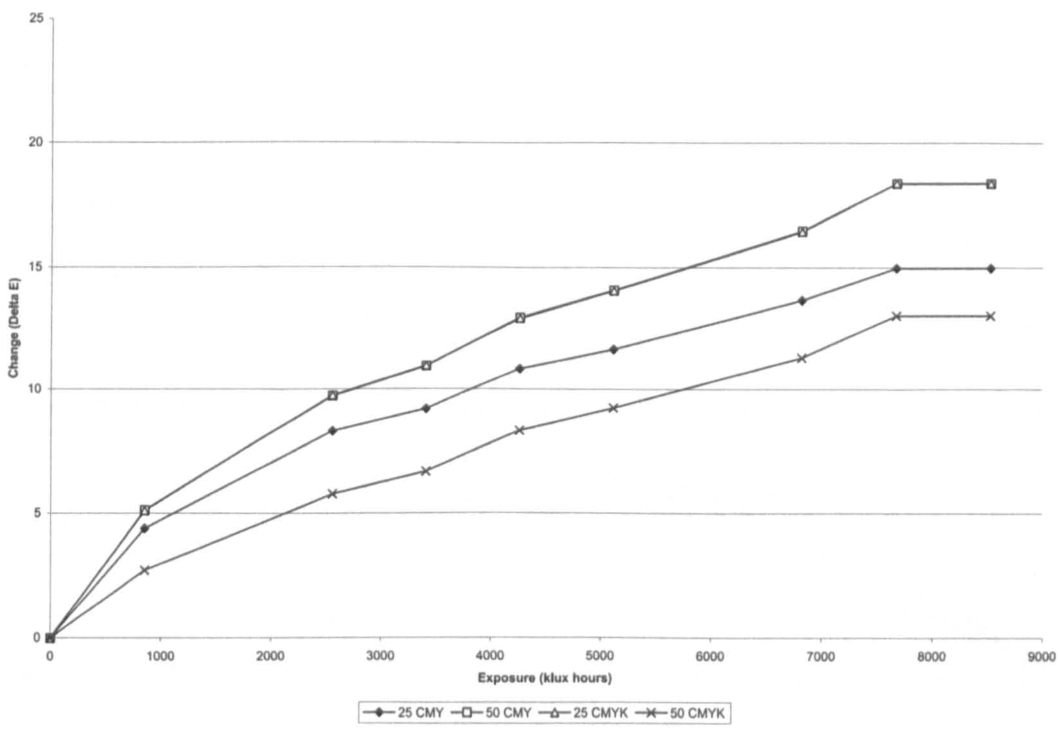
J.19 Bar chart showing the change in ΔEab of the primary inks printed in different concentrations Epson Pro 9000 ink set printed on Whatman watercolour paper (3.4) exposed to the fluorescent light fastness tester under an UV filter.



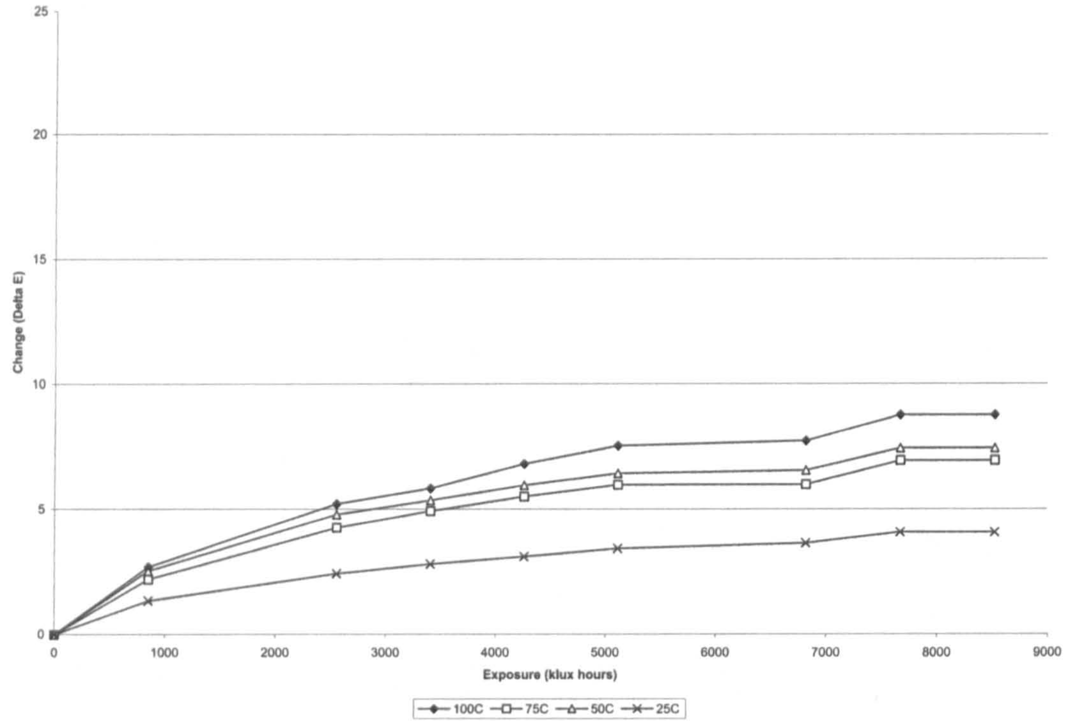
J.20 Plot showing the change in ΔEab against exposure of the CMYK ink patches from the Epson Pro 9000 ink set printed on Whatman watercolour paper (3.4) exposed to the fluorescent light fastness tester under an UV filter.



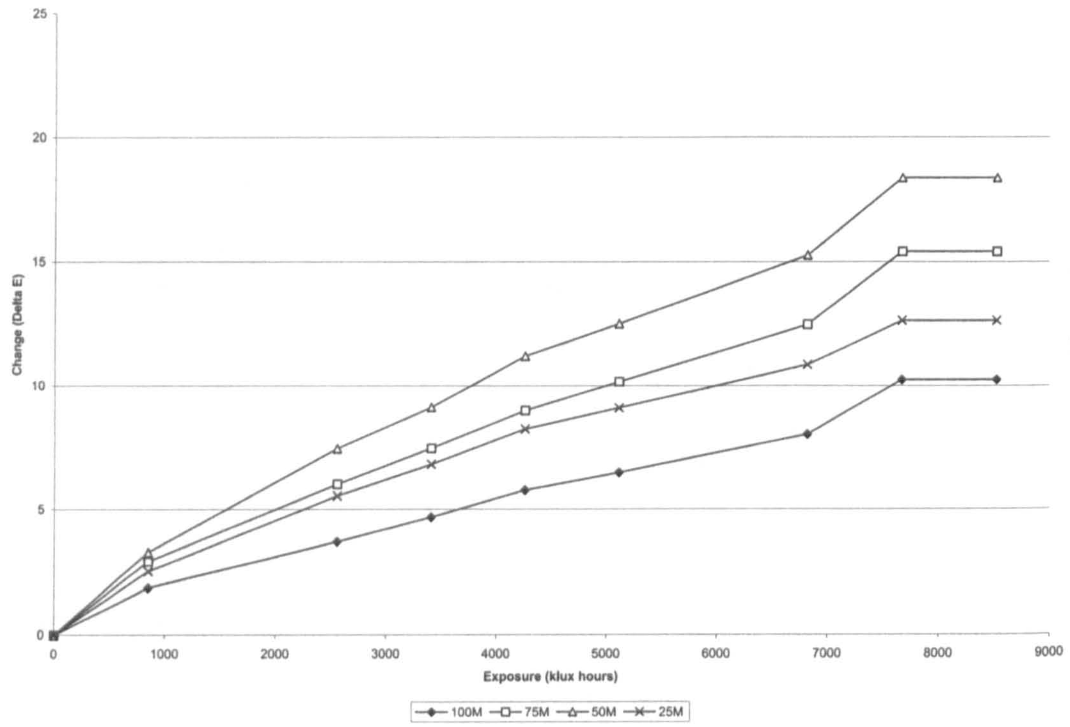
J.21 Plot showing the change in ΔEab against exposure of the RGB ink patches from the Epson Pro 9000 ink set printed on Whatman watercolour paper (3.4) exposed to the fluorescent light fastness tester under an UV filter.



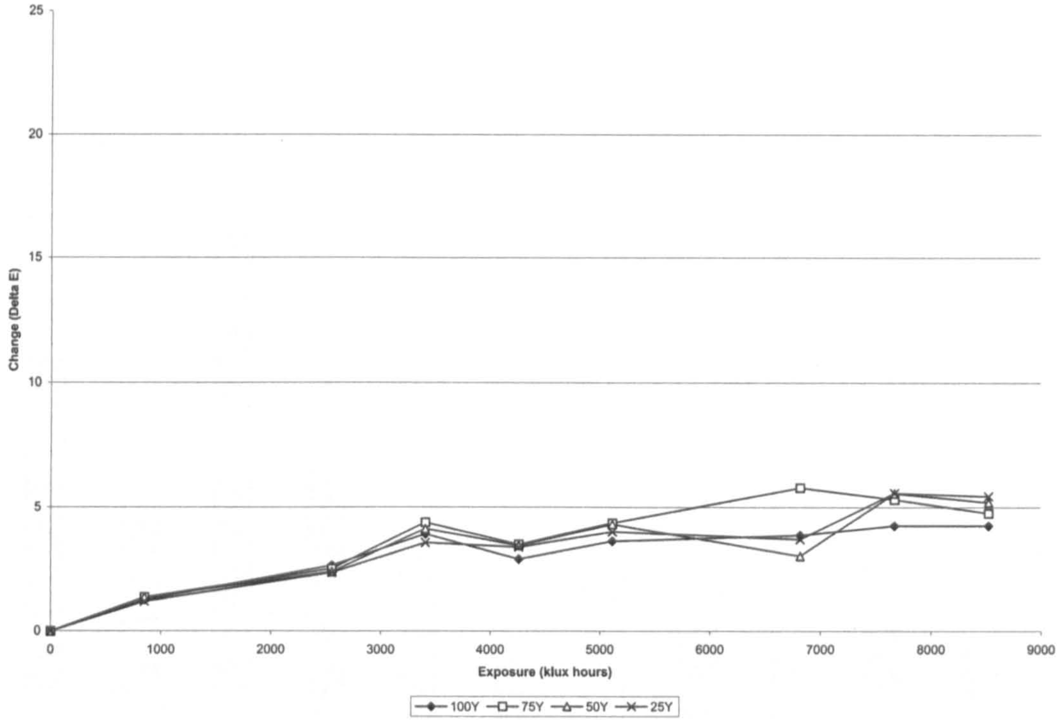
J.22 Plot showing the change in ΔEab against exposure of the 25 % and 50 % printed grey scales from the Epson Pro 9000 ink set produced on Whatman watercolour paper (3.4) exposed to the fluorescent light fastness tester under an UV filter.



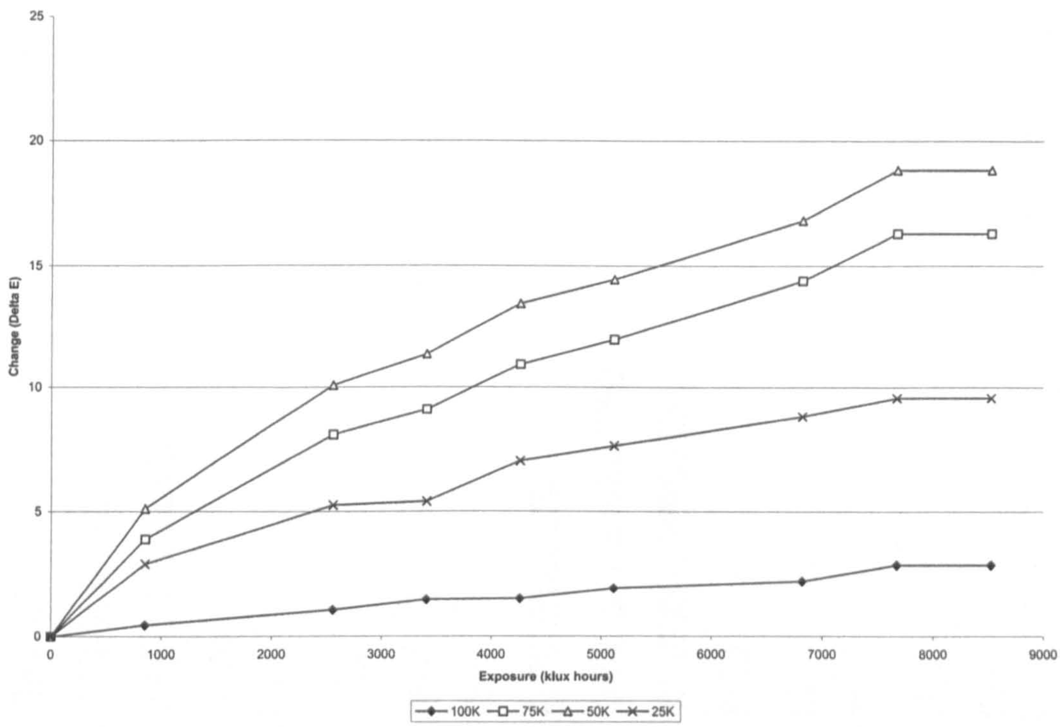
J.23 Plot showing the change in ΔEab against exposure of the cyan ink from the Epson Pro 9000 ink set printed in different concentrations on Whatman watercolour paper (3.4) exposed to the fluorescent light fastness tester under an UV filter.



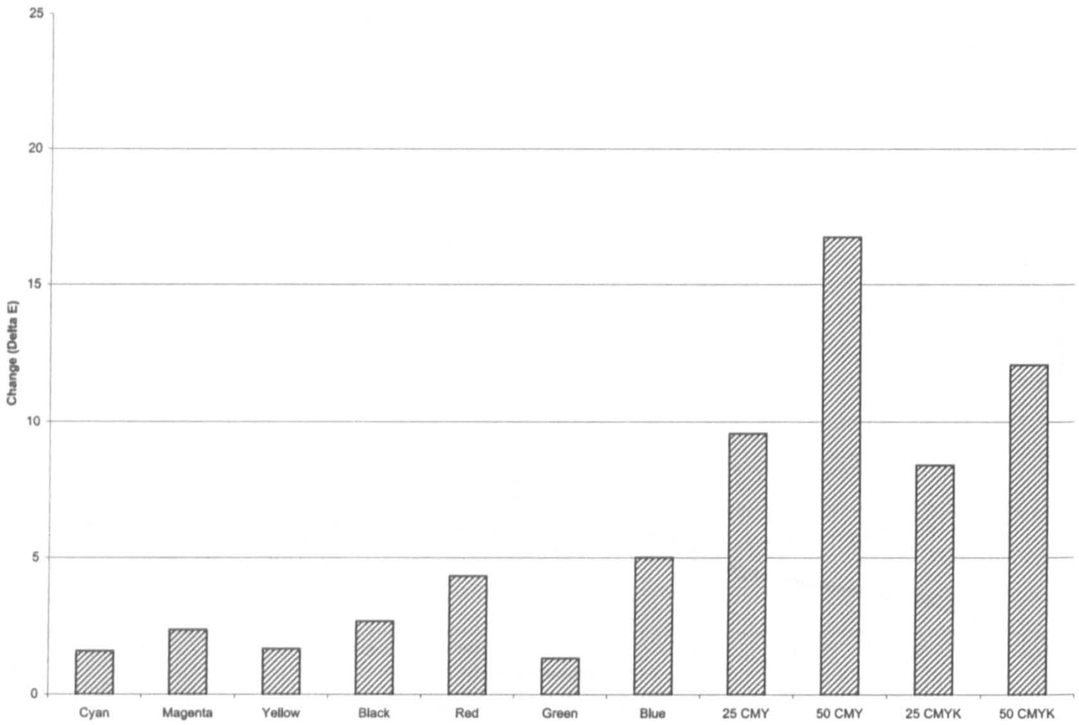
J.24 Plot showing the change in ΔEab against exposure of the magenta ink from the Epson Pro 9000 ink set printed in different concentrations on Whatman watercolour paper (3.4) exposed to the fluorescent light fastness tester under an UV filter.



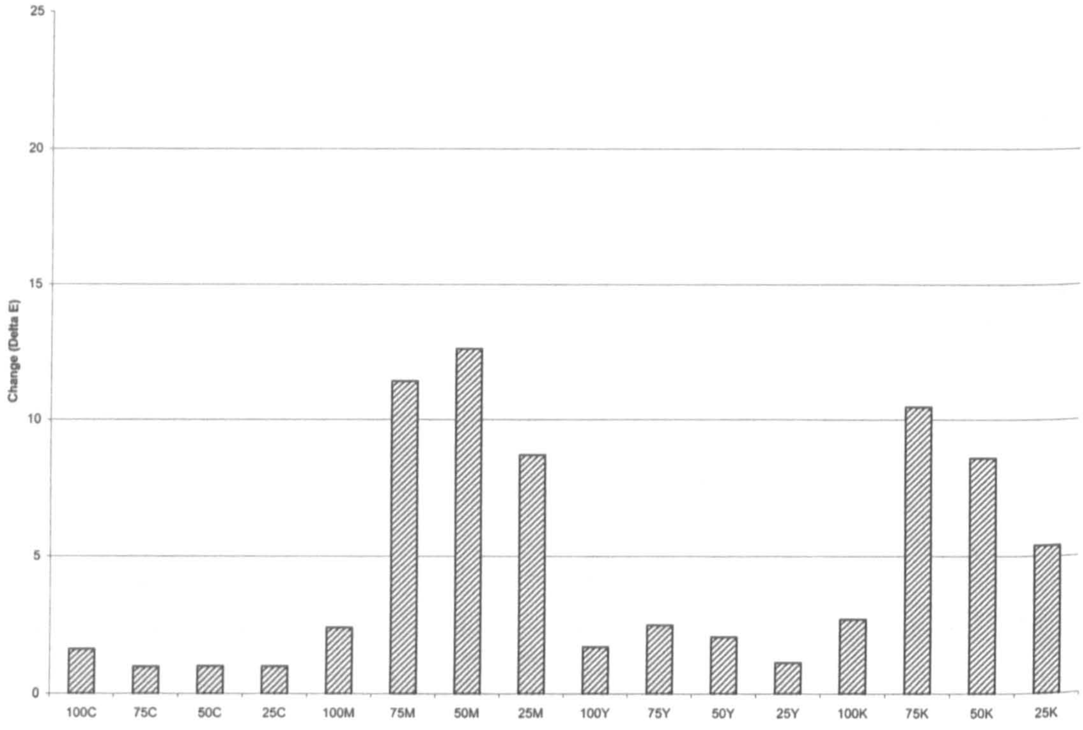
J.25 Plot showing the change in ΔEab against exposure of the yellow ink from the Epson Pro 9000 ink set printed in different concentrations on Whatman watercolour paper (3.4) exposed to the fluorescent light fastness tester under an UV filter.



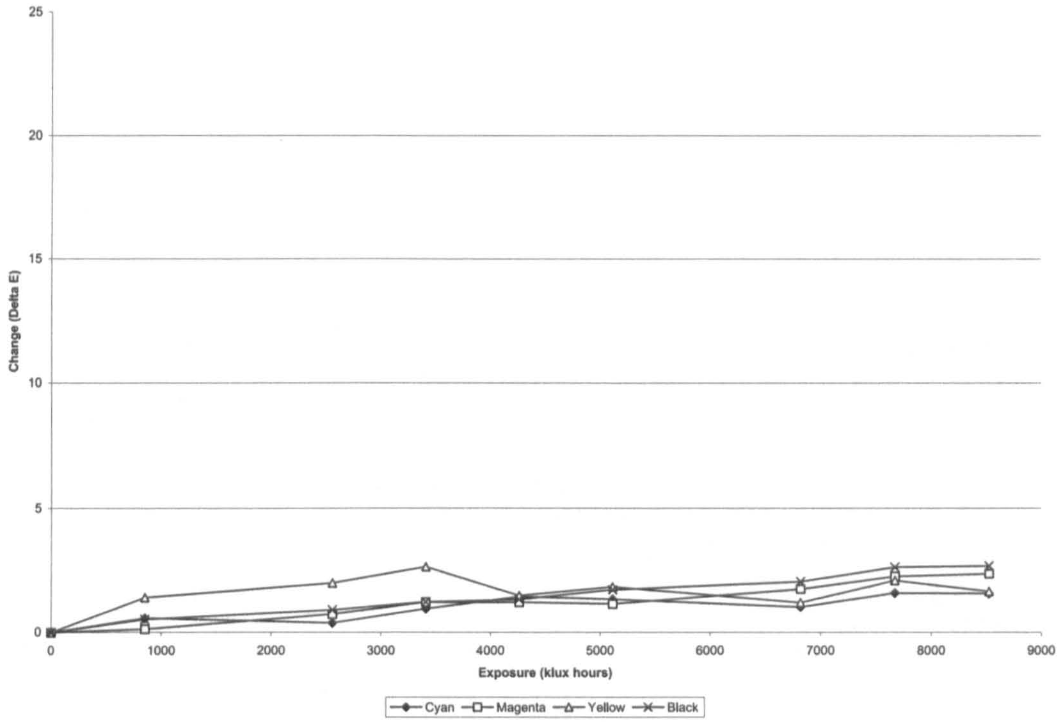
J.26 Plot showing the change in ΔEab against exposure of the black ink from the Epson Pro 9000 ink set printed in different concentrations on Whatman watercolour paper (3.4) exposed to the fluorescent light fastness tester under an UV filter.



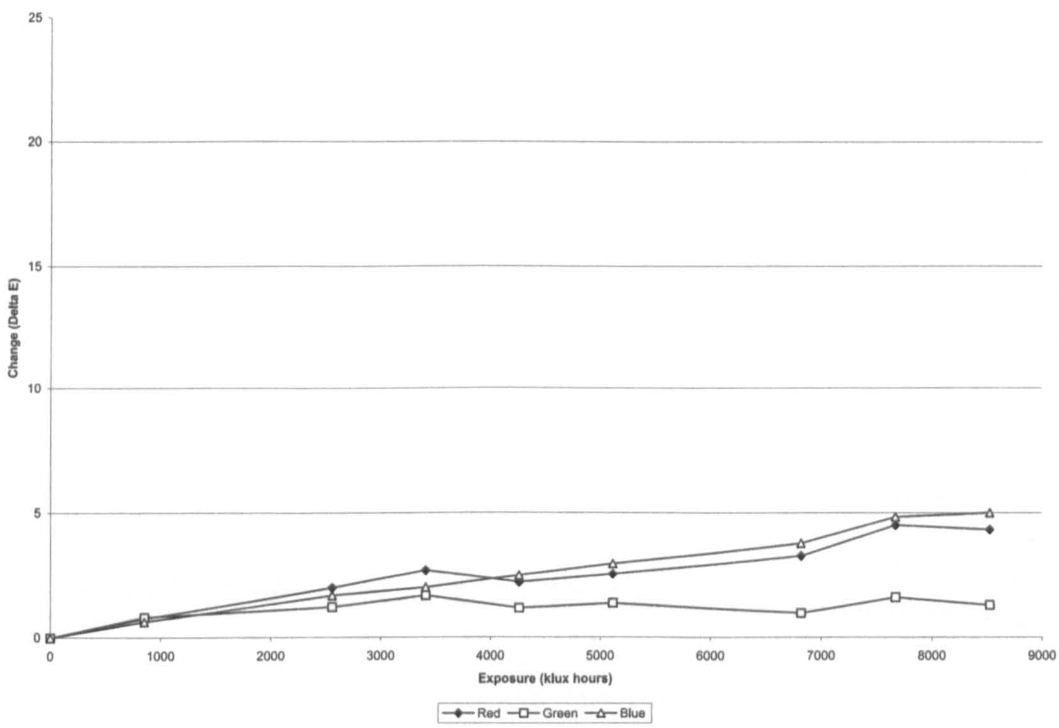
J.27 Bar chart showing the change in ΔEab of the primary inks and their combinations Epson Pro 9000 ink set printed on the Epson Presentation Matt paper (3.5) exposed to the fluorescent light fastness tester under an UV filter.



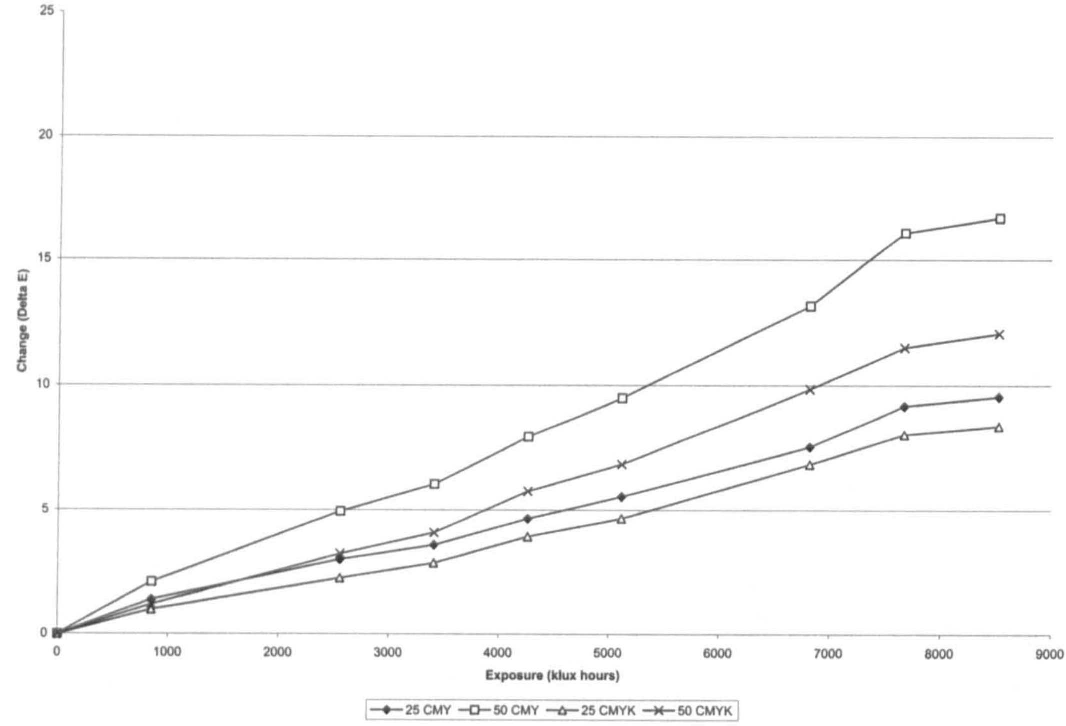
J.28 Bar chart showing the change in ΔEab of the primary inks printed in different concentrations Epson Pro 9000 ink set printed on the Epson Presentation Matt paper (3.5) exposed to the fluorescent light fastness tester under an UV filter.



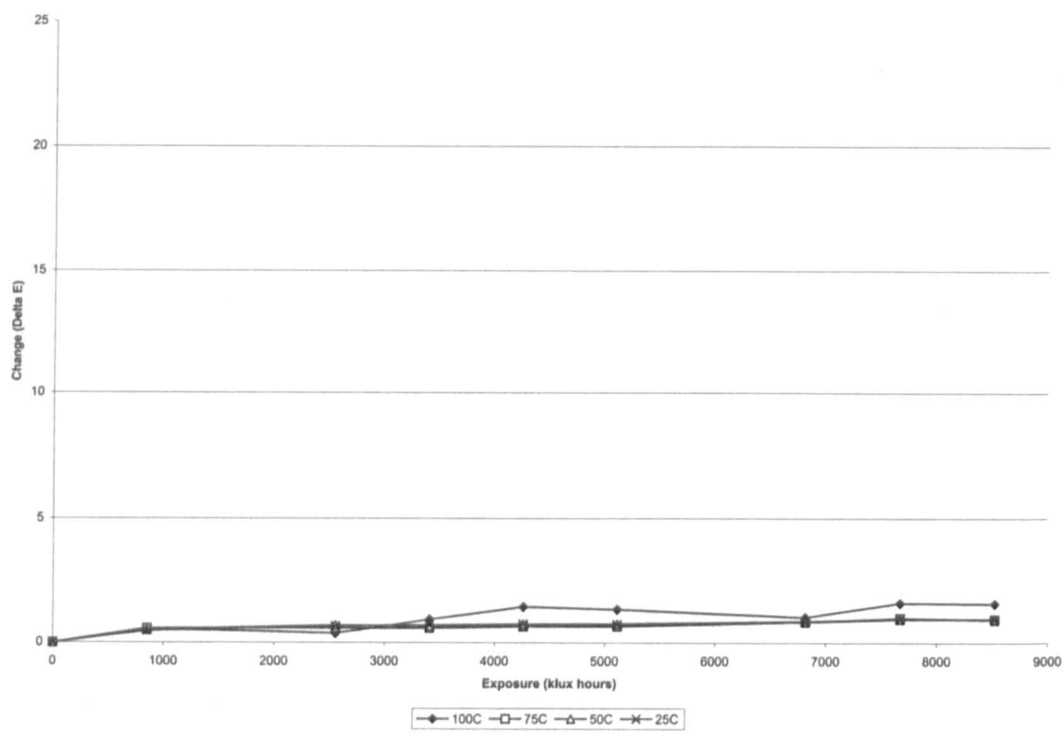
J.29 Plot showing the change in ΔEab against exposure of the CMYK ink patches from the Epson Pro 9000 ink set printed on the Epson Presentation Matt paper (3.5) exposed to the fluorescent light fastness tester under an UV filter.



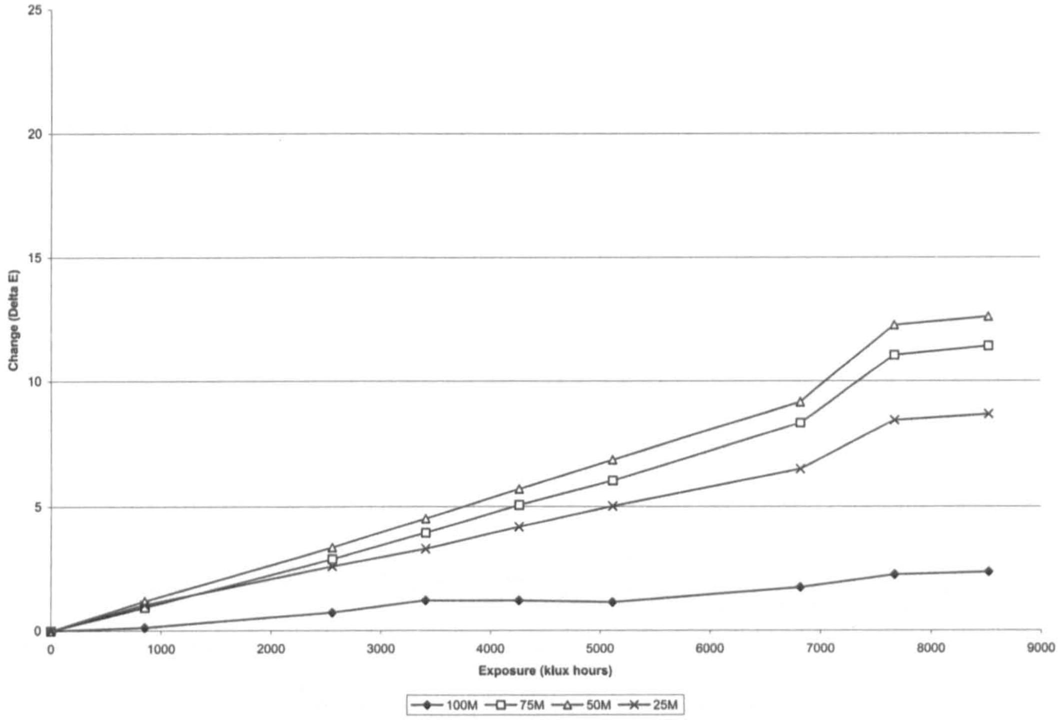
J.30 Plot showing the change in ΔEab against exposure of the RGB ink patches from the Epson Pro 9000 ink set printed on the Epson Presentation Matt paper (3.5) exposed to the fluorescent light fastness tester under an UV filter.



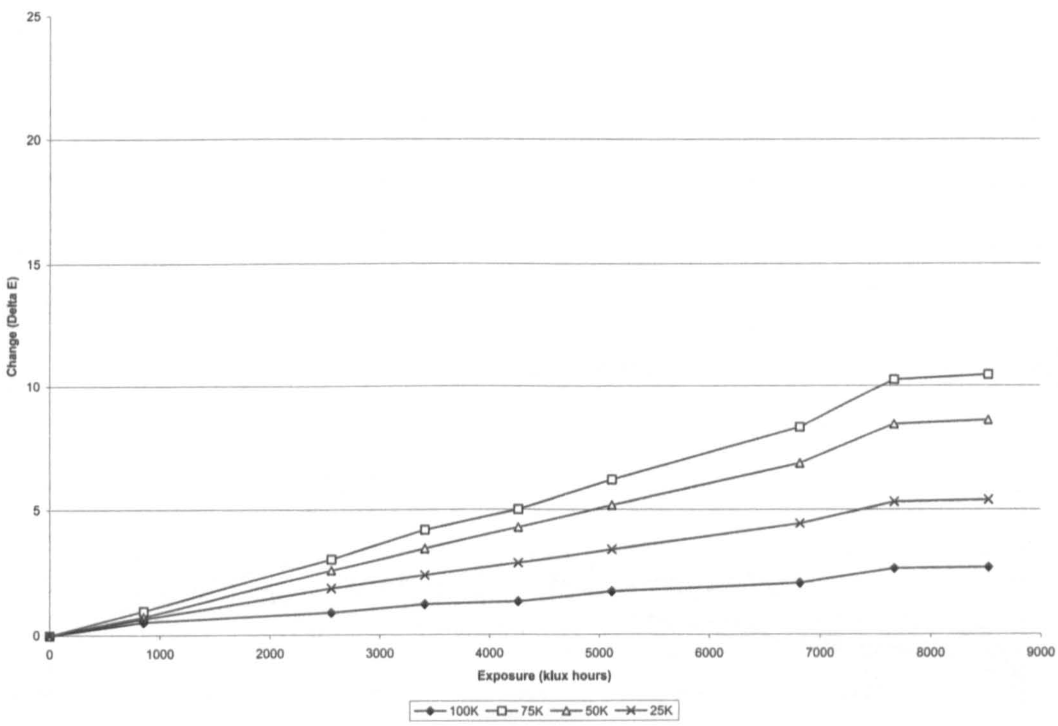
J.31 Plot showing the change in ΔEab against exposure of the 25 % and 50 % printed grey scales from the Epson Pro 9000 ink set produced on the Epson Presentation Matt paper (3.5) exposed to the fluorescent light fastness tester under an UV filter.



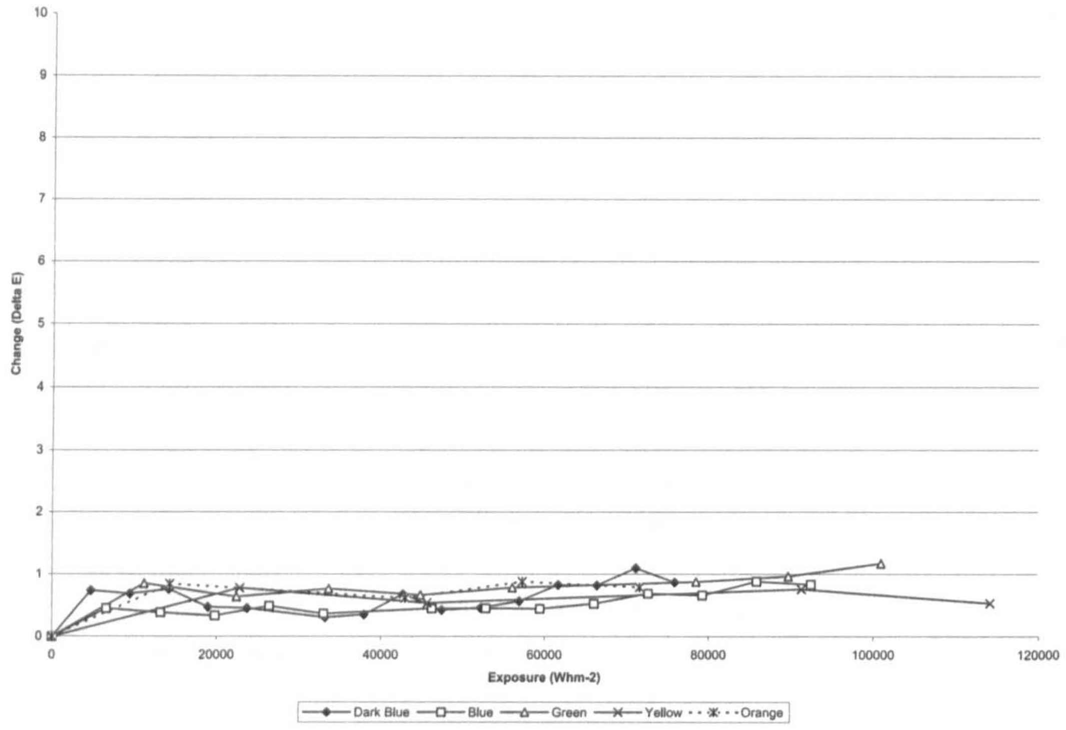
J.32 Plot showing the change in ΔEab against exposure of the cyan ink from the Epson Pro 9000 ink set printed in different concentrations on the Epson Presentation Matt paper (3.5) exposed to thefluorescent light fastness tester under an UV filter.



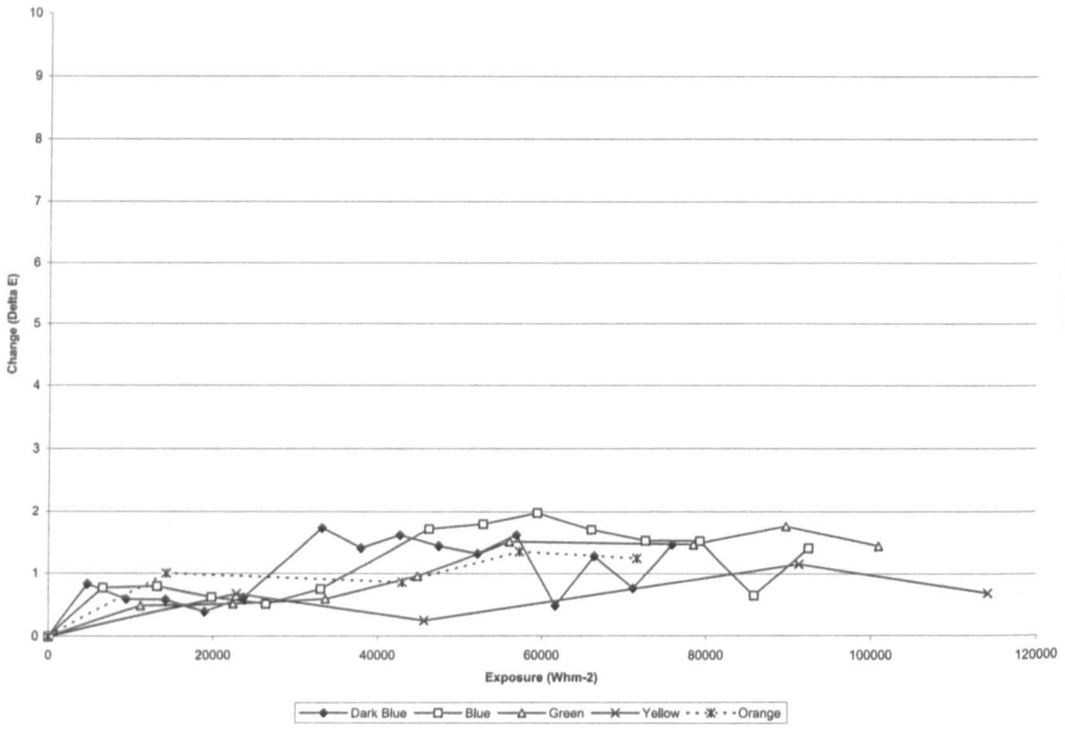
J.33 Plot showing the change in ΔEab against exposure of the magenta ink from the Epson Pro 9000 ink set printed in different concentrations on the Epson Presentation Matt paper (3.5) exposed to the fluorescent light fastness tester under an UV filter.



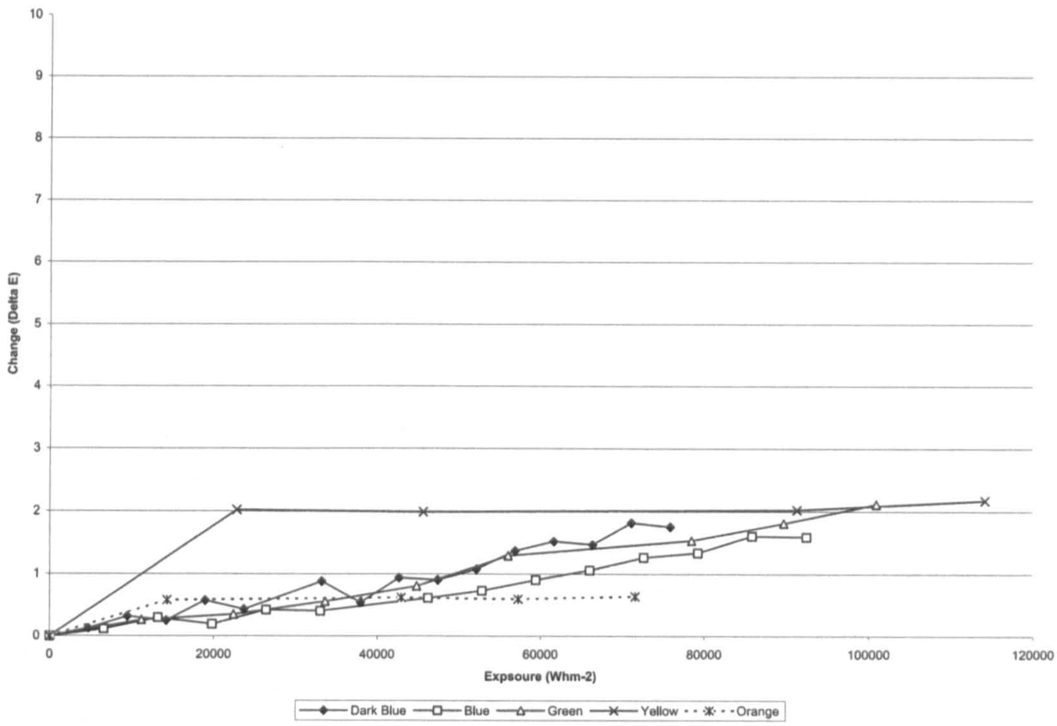
J.34 Plot showing the change in ΔEab against exposure of the black ink from the Epson Pro 9000 ink set printed in different concentrations on the Epson Presentation Matt paper (3.5) exposed to the fluorescent light fastness tester under an UV filter.



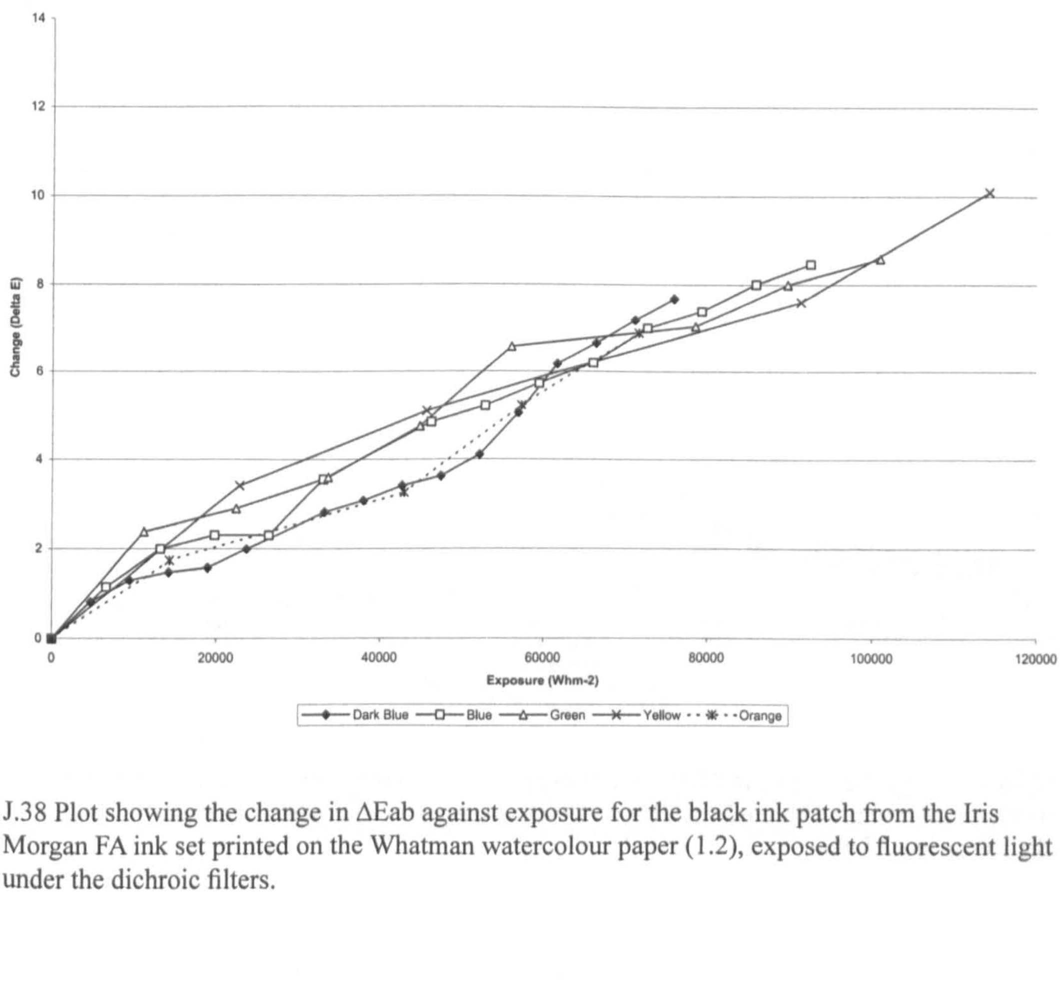
J.35 Plot showing the change in ΔEab against exposure for the yellow ink patch from the Iris Morgan FA ink set printed on the Somerset Velvet paper (1.1), exposed to fluorescent light under the dichroic filters.



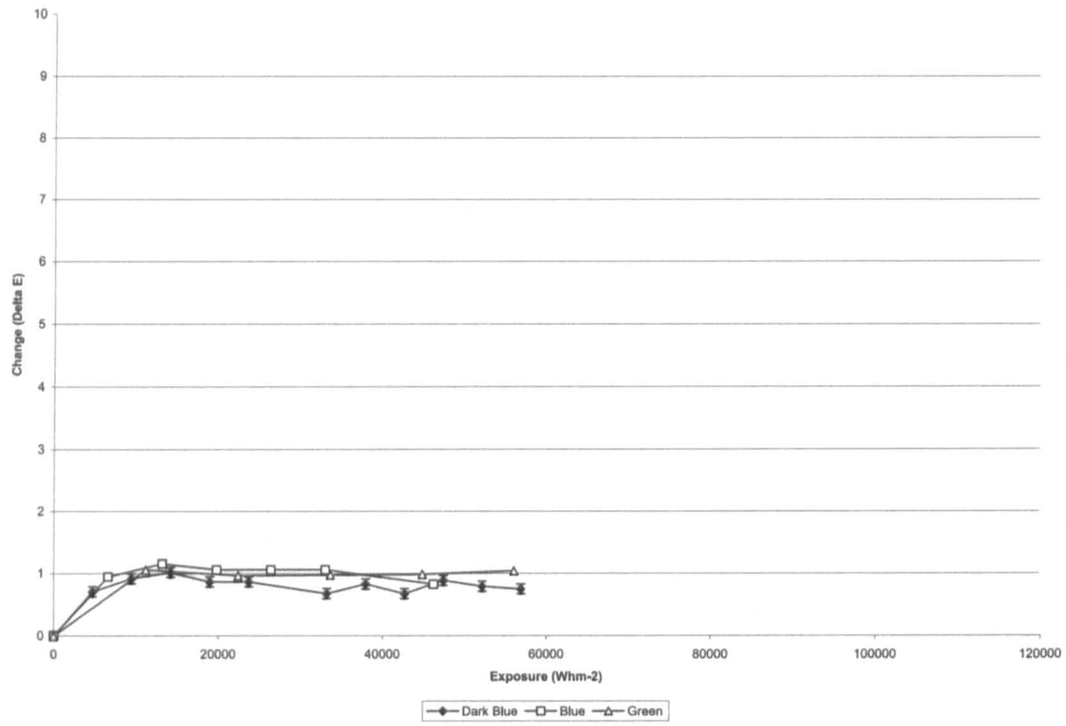
J.36 Plot showing the change in ΔEab against exposure for the cyan ink patch from the Iris Morgan FA ink set printed on the Whatman watercolour paper (1.2), exposed to fluorescent light under the dichroic filters.



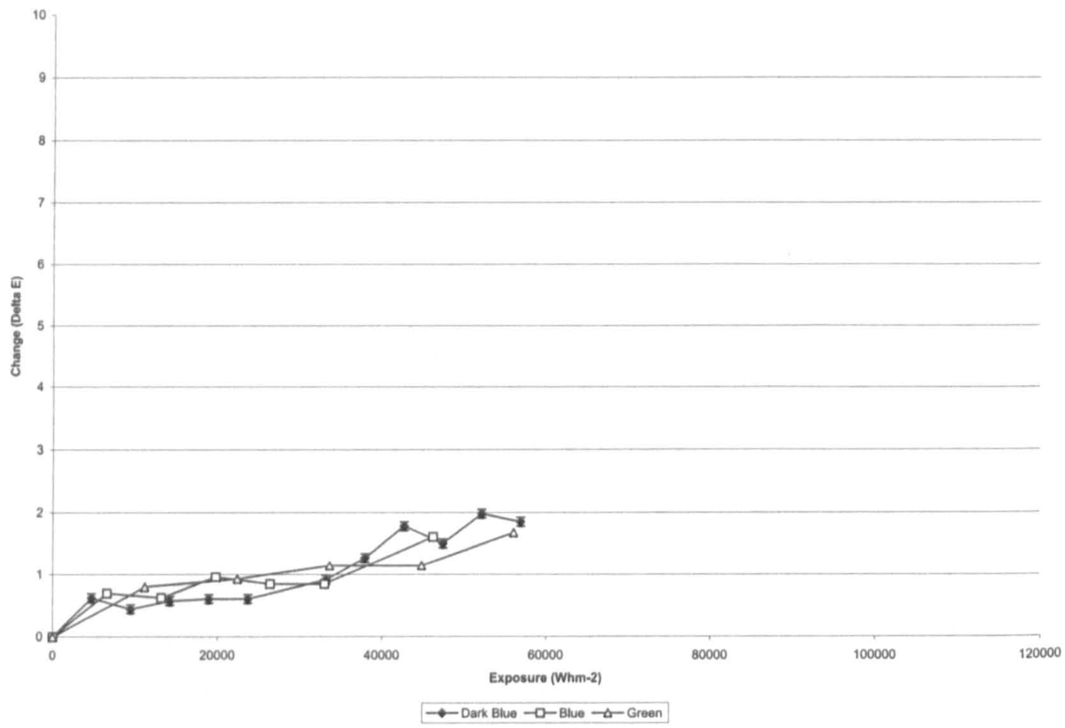
J.37 Plot showing the change in ΔEab against exposure for the yellow ink patch from the Iris Morgan FA ink set printed on the Whatman watercolour paper (1.2), exposed to fluorescent light under the dichroic filters.



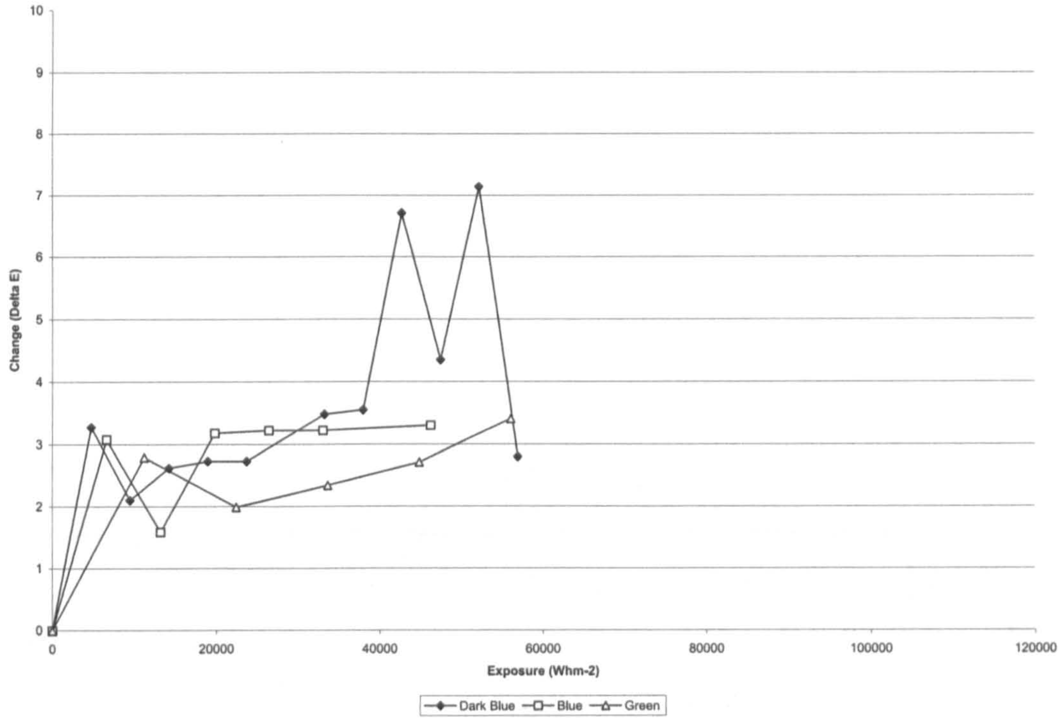
J.38 Plot showing the change in ΔEab against exposure for the black ink patch from the Iris Morgan FA ink set printed on the Whatman watercolour paper (1.2), exposed to fluorescent light under the dichroic filters.



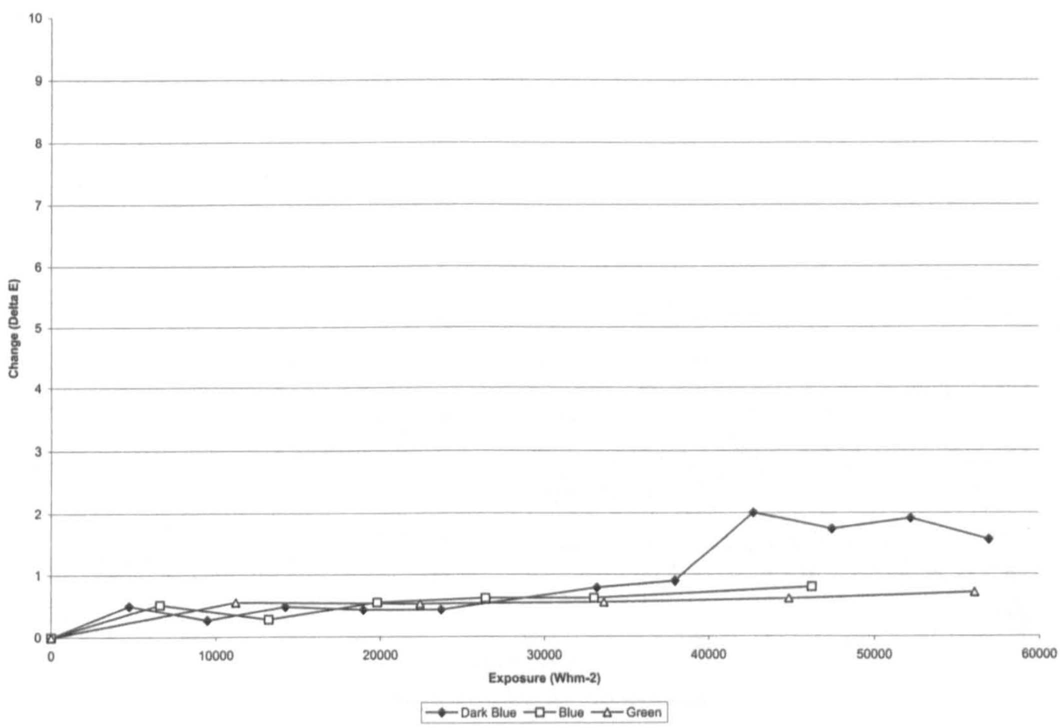
J.39 Plot showing the change in ΔEab against exposure for the cyan ink patch from the Epson Pro 9000 ink set printed on the Epson Photo Glossy paper (3.1), exposed to fluorescent light under the dichroic filters.



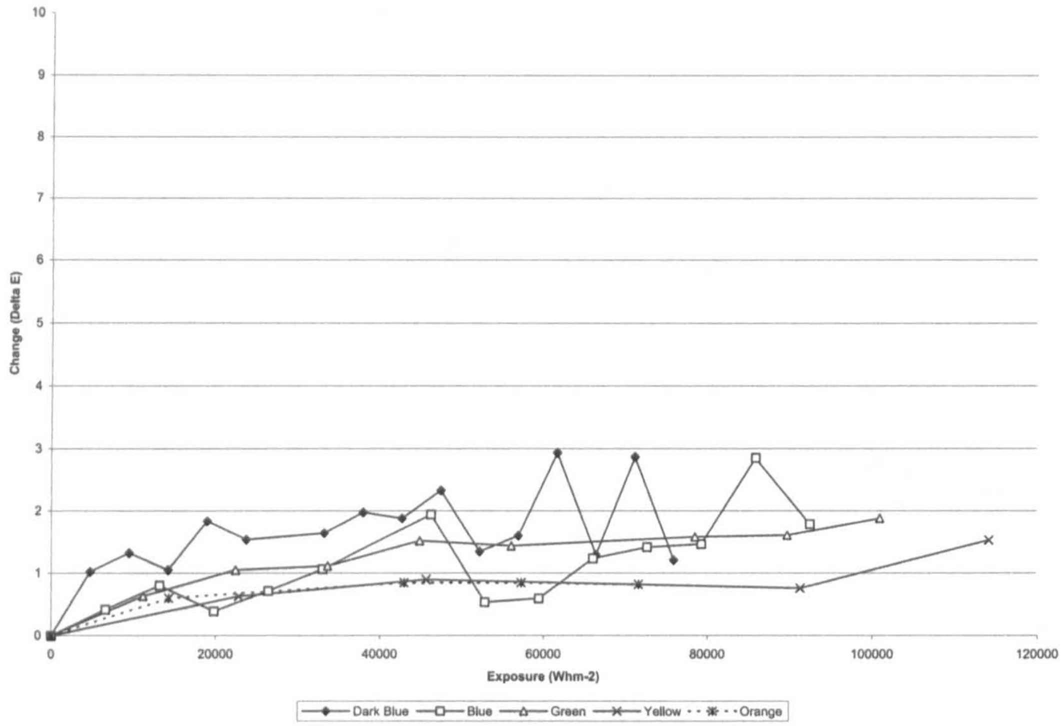
J.40 Plot showing the change in ΔEab against exposure for the magenta ink patch from the Epson Pro 9000 ink set printed on the Epson Photo Glossy paper (3.1), exposed to fluorescent light under the dichroic filters.



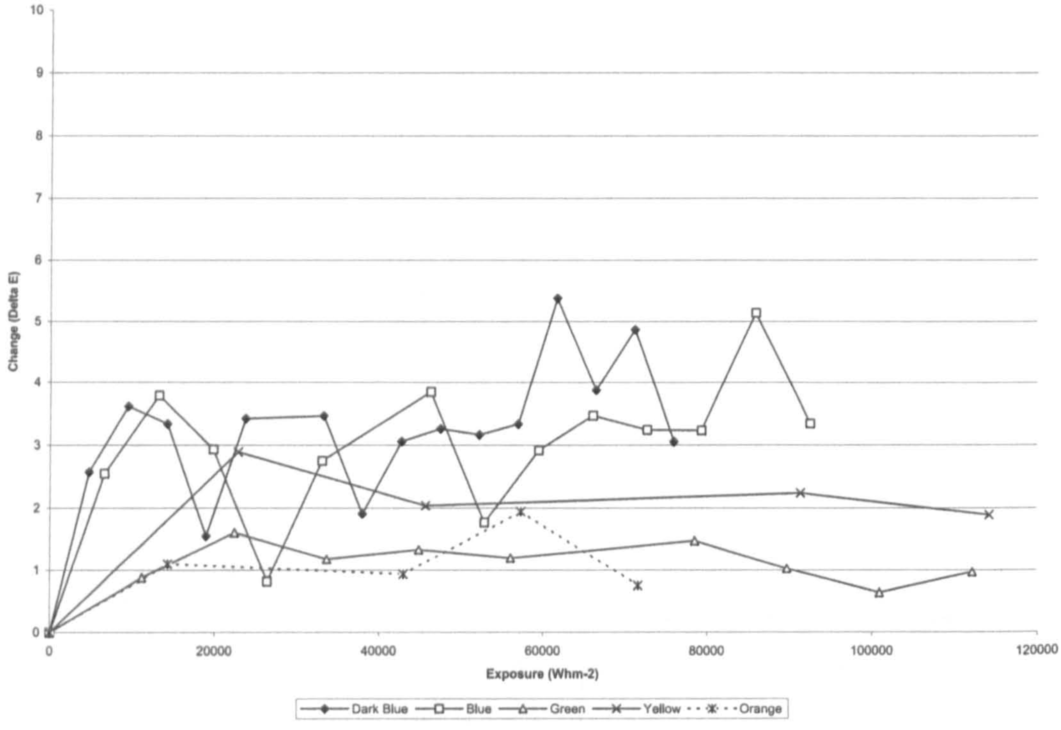
J.41 Plot showing the change in ΔEab against exposure for the yellow ink patch from the Epson Pro 9000 ink set printed on the Epson Photo Glossy paper (3.1), exposed to fluorescent light under the dichroic filters.



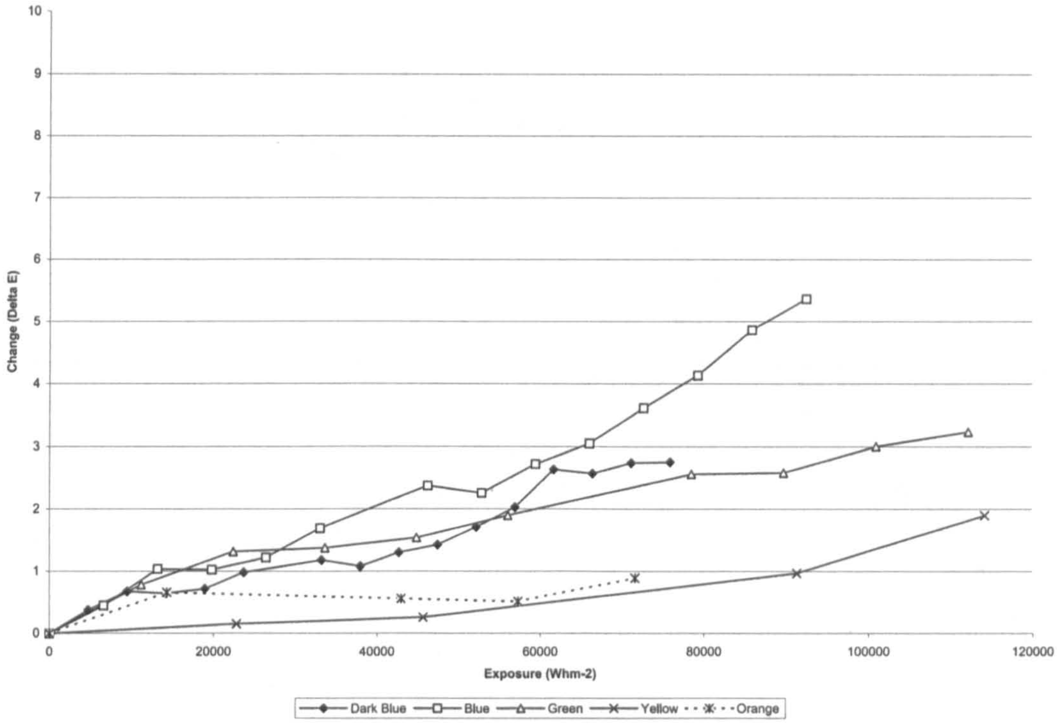
J.42 Plot showing the change in ΔEab against exposure for the black ink patch from the Epson Pro 9000 ink set printed on the Epson Photo Glossy paper (3.1), exposed to fluorescent light under the dichroic filters.



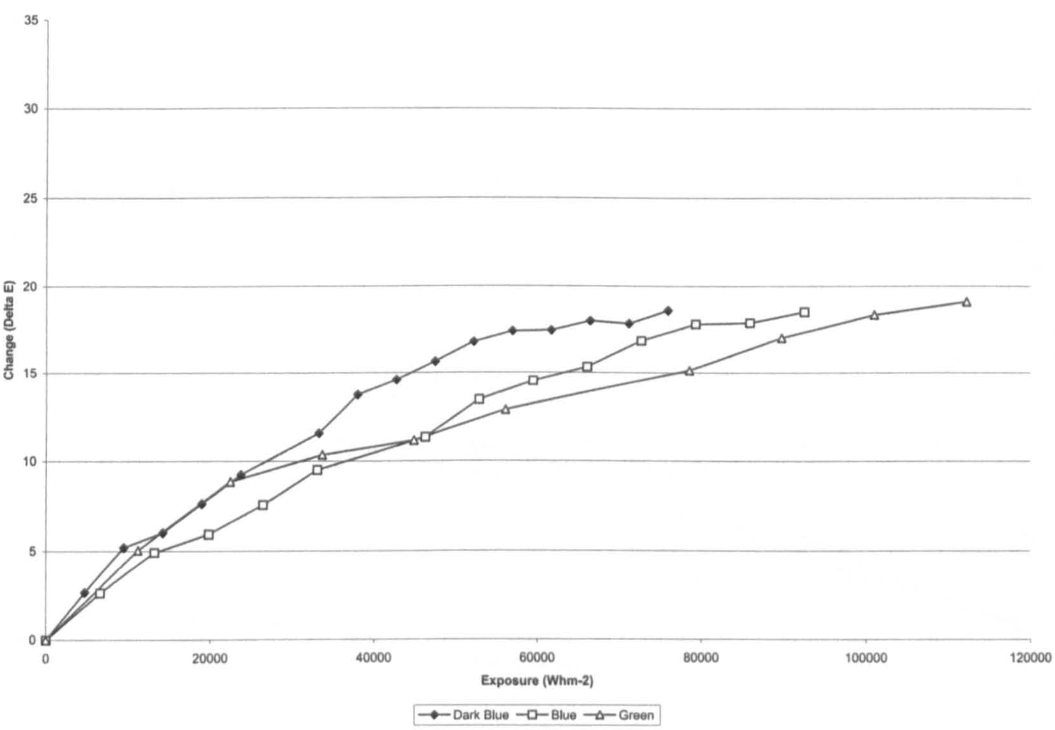
J.43 Plot showing the change in ΔEab against exposure for the cyan ink patch from the Epson Pro 9000 ink set printed on the ISVE paper (3.2), exposed to fluorescent light under the dichroic filters.



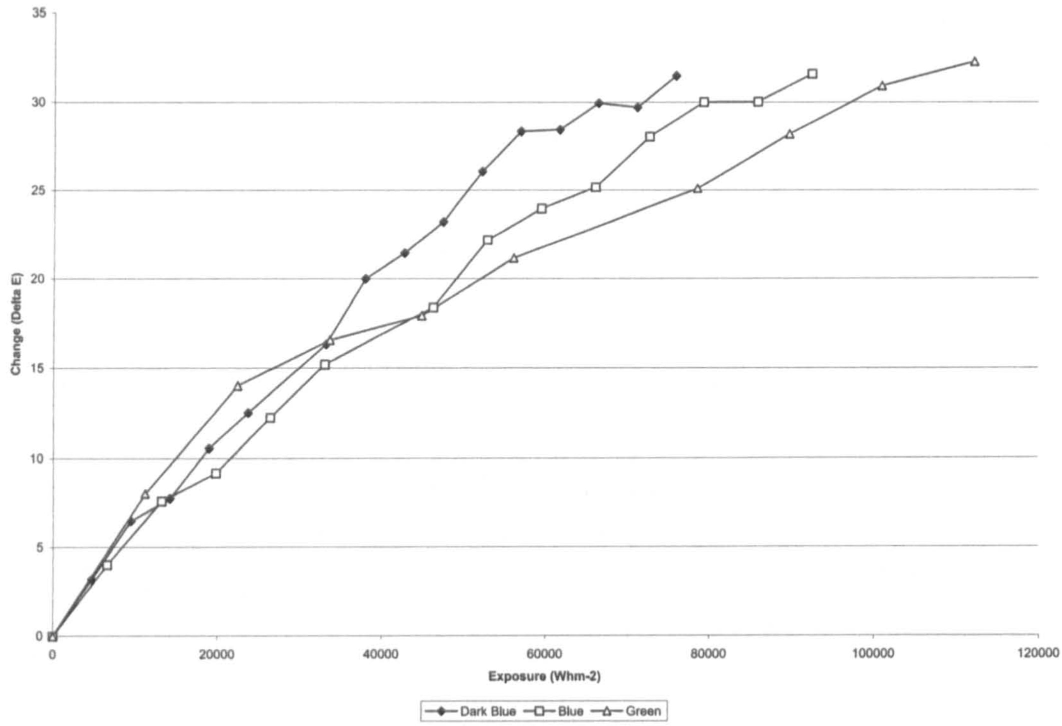
J.44 Plot showing the change in ΔEab against exposure for the yellow ink patch from the Epson Pro 9000 ink set printed on the ISVE paper (3.2), exposed to fluorescent light under the dichroic filters.



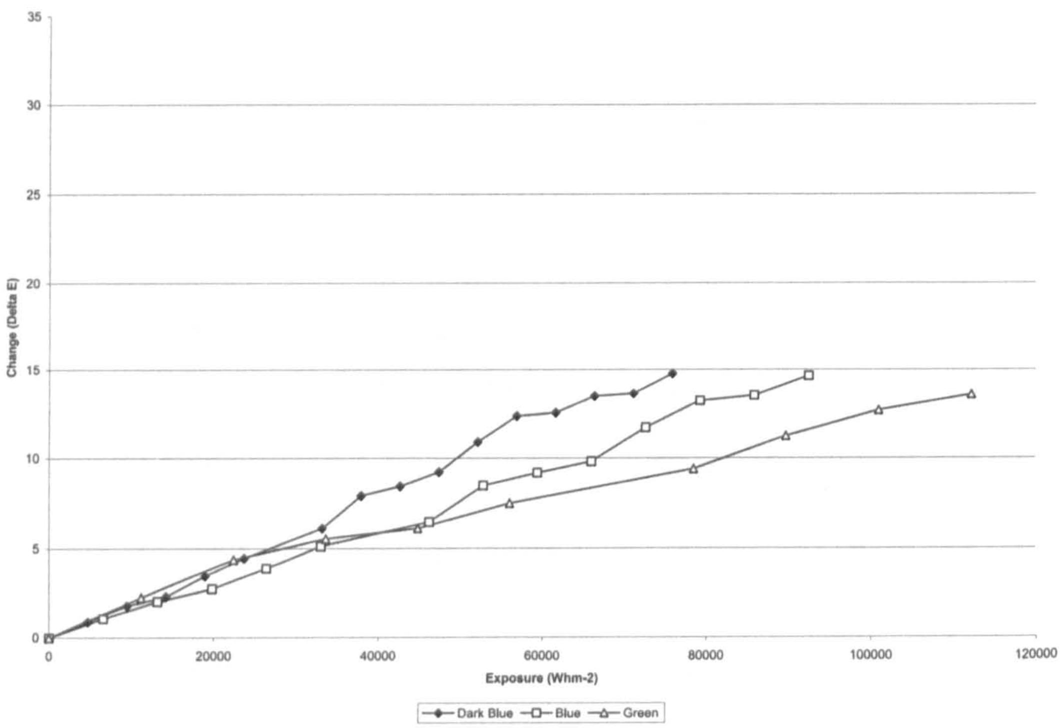
J.45 Plot showing the change in ΔEab against exposure for the black ink patch from the Epson Pro 9000 ink set printed on the ISVE paper (3.2), exposed to fluorescent light under the dichroic filters.



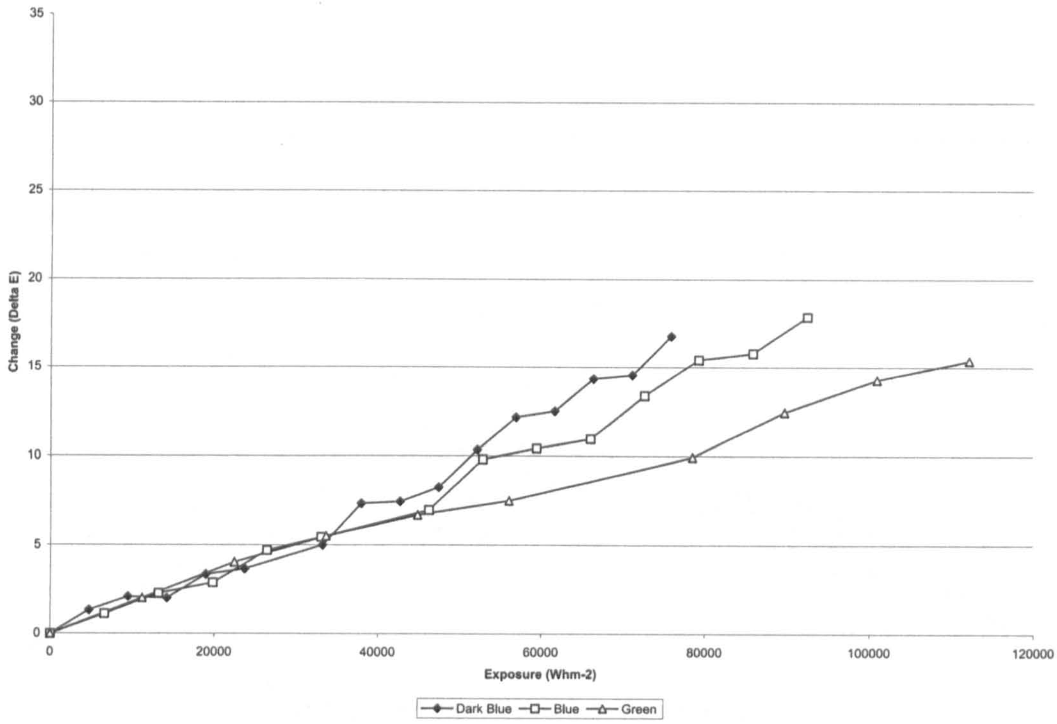
J.46 Plot showing the change in ΔEab against exposure for the 25 % CMY ink patch from the Epson Pro 9000 ink set printed on the ISVE paper (3.2), exposed to fluorescent light under the dichroic filters.



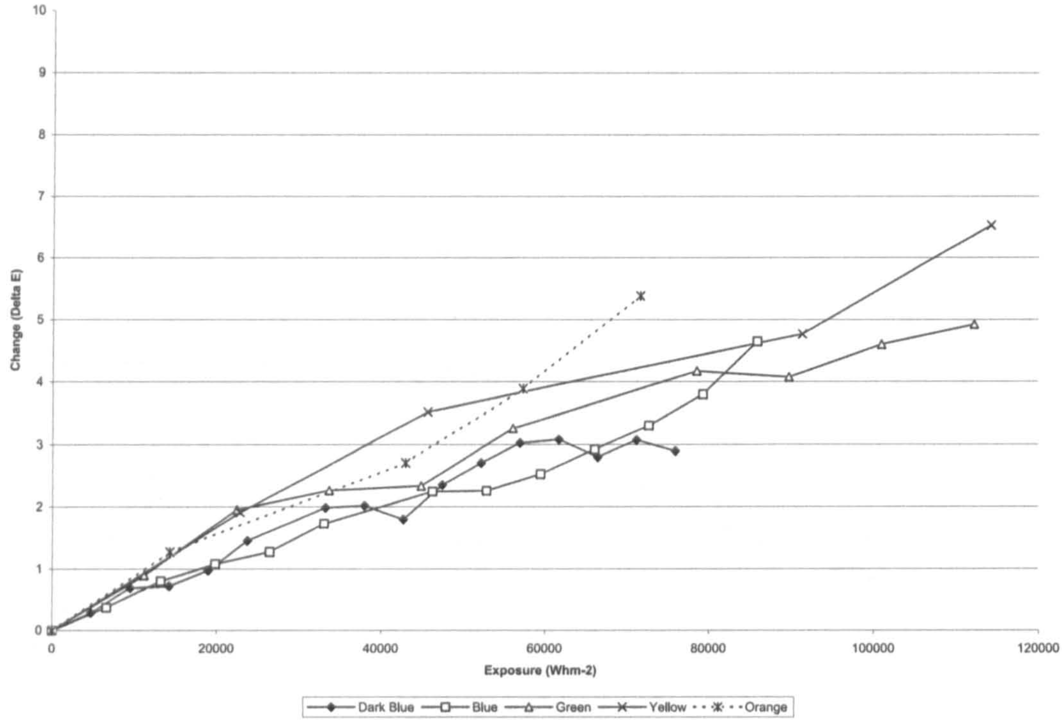
J.47 Plot showing the change in ΔEab against exposure for the 50 % CMY ink patch from the Epson Pro 9000 ink set printed on the ISVE paper (3.2), exposed to fluorescent light under the dichroic filters.



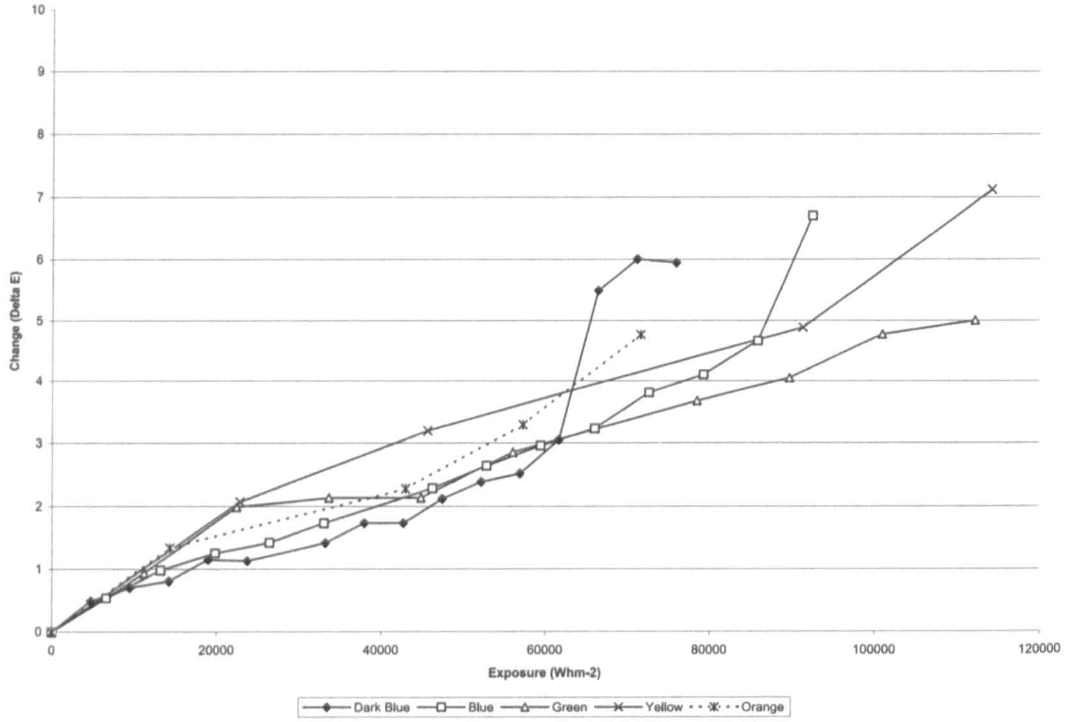
J.48 Plot showing the change in ΔEab against exposure for the 25 % CMYK ink patch from the Epson Pro 9000 ink set printed on the ISVE paper (3.2), exposed to fluorescent light under the dichroic filters.



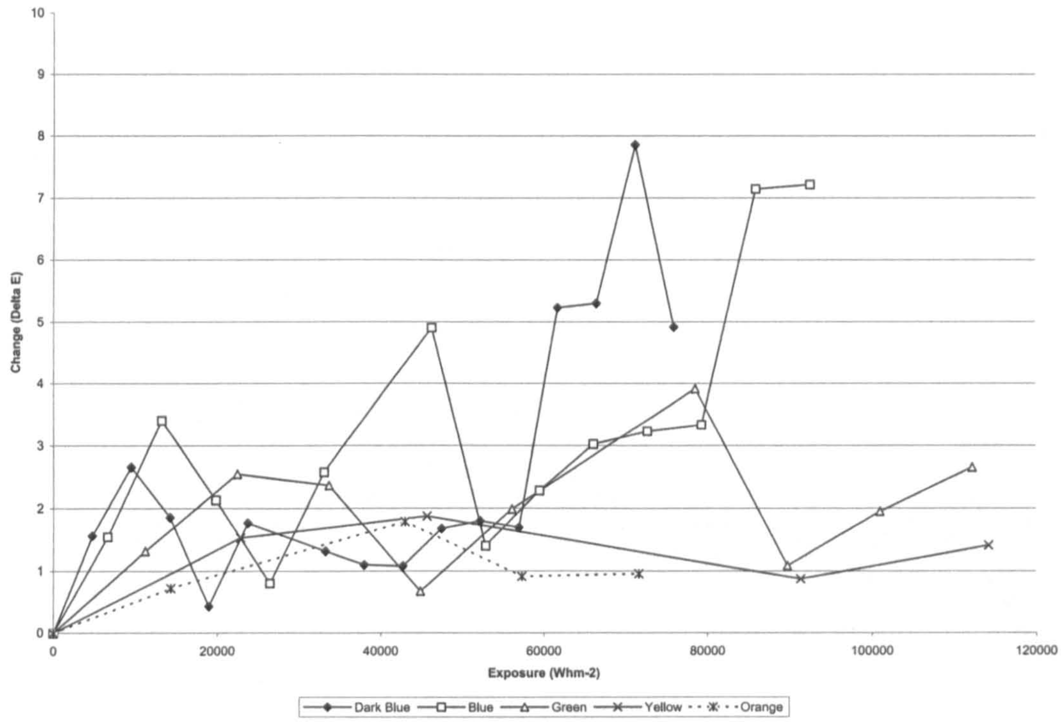
J.49 Plot showing the change in ΔEab against exposure for the 50 % CMYK ink patch from the Epson Pro 9000 ink set printed on the ISVE paper (3.2), exposed to fluorescent light under the dichroic filters.



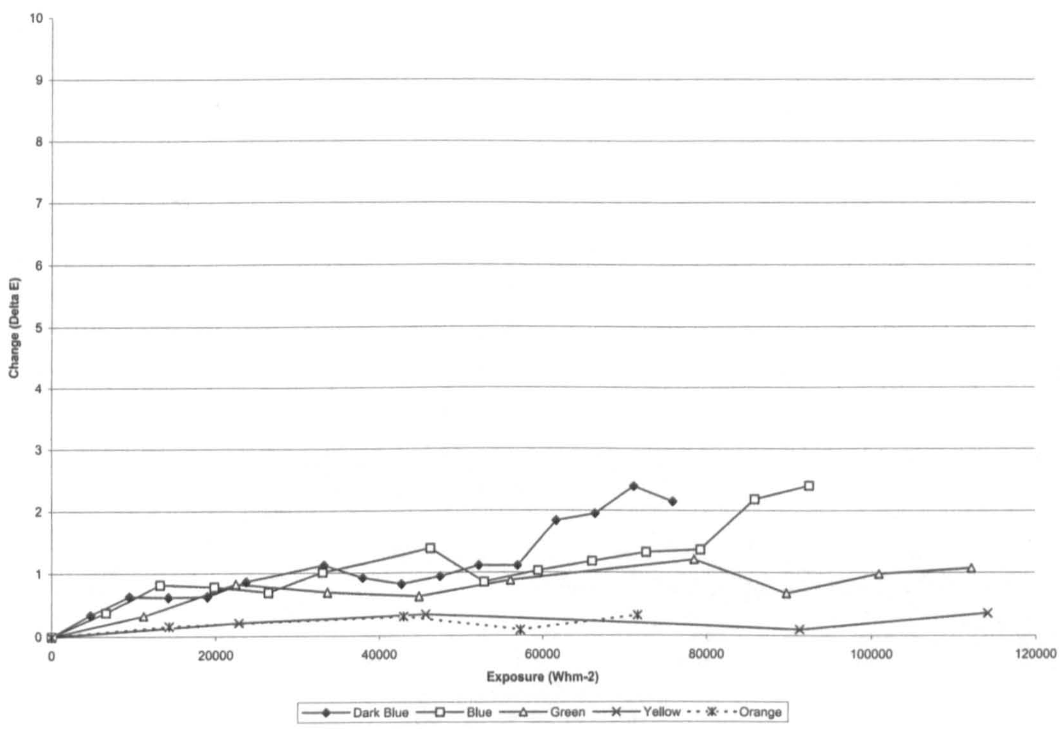
J.50 Plot showing the change in ΔEab against exposure for the cyan ink patch from the Epson Pro 9000 ink set printed on the Somerset Velvet paper (3.3), exposed to fluorescent light under the dichroic filters.



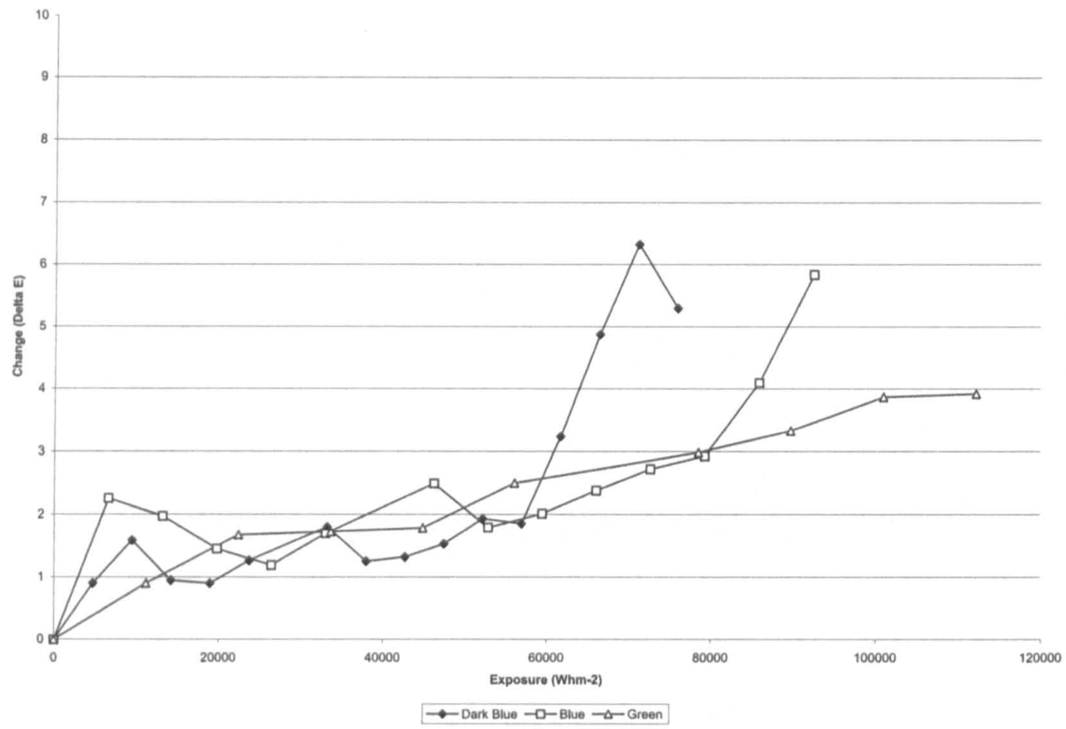
J.51 Plot showing the change in ΔEab against exposure for the magenta ink patch from the Epson Pro 9000 ink set printed on the Somerset Velvet paper (3.3), exposed to fluorescent light under the dichroic filters.



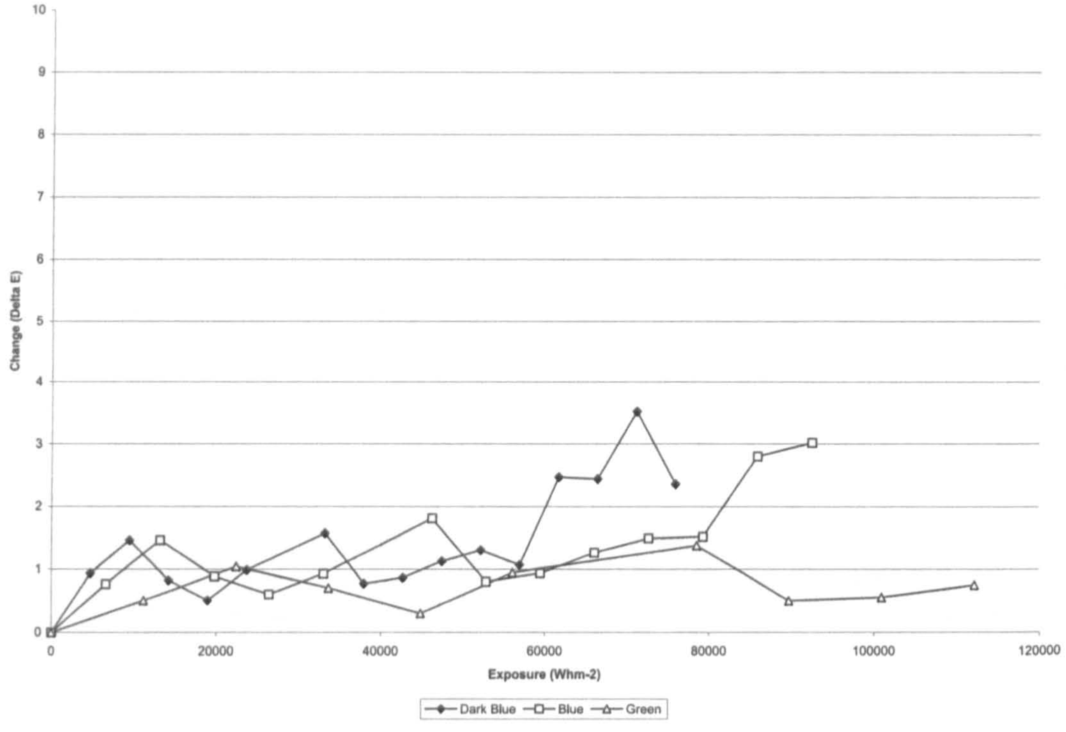
J.52 Plot showing the change in ΔEab against exposure for the yellow ink patch from the Epson Pro 9000 ink set printed on the Somerset Velvet paper (3.3), exposed to fluorescent light under the dichroic filters.



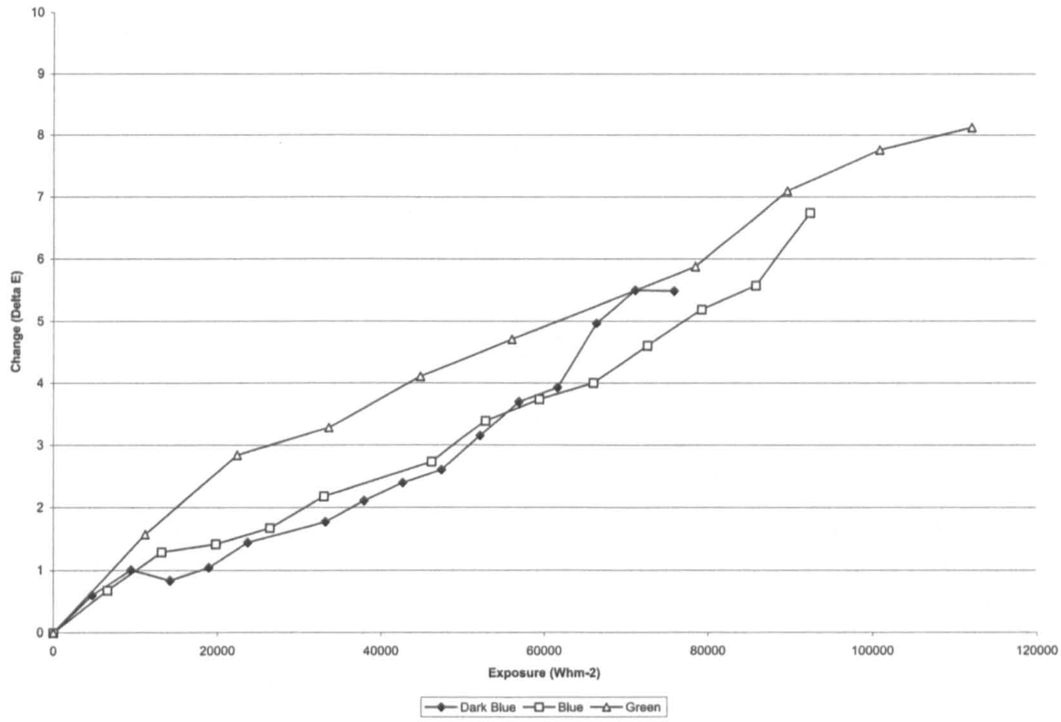
J.53 Plot showing the change in ΔEab against exposure for the black ink patch from the Epson Pro 9000 ink set printed on the Somerset Velvet paper (3.3), exposed to fluorescent light under the dichroic filters.



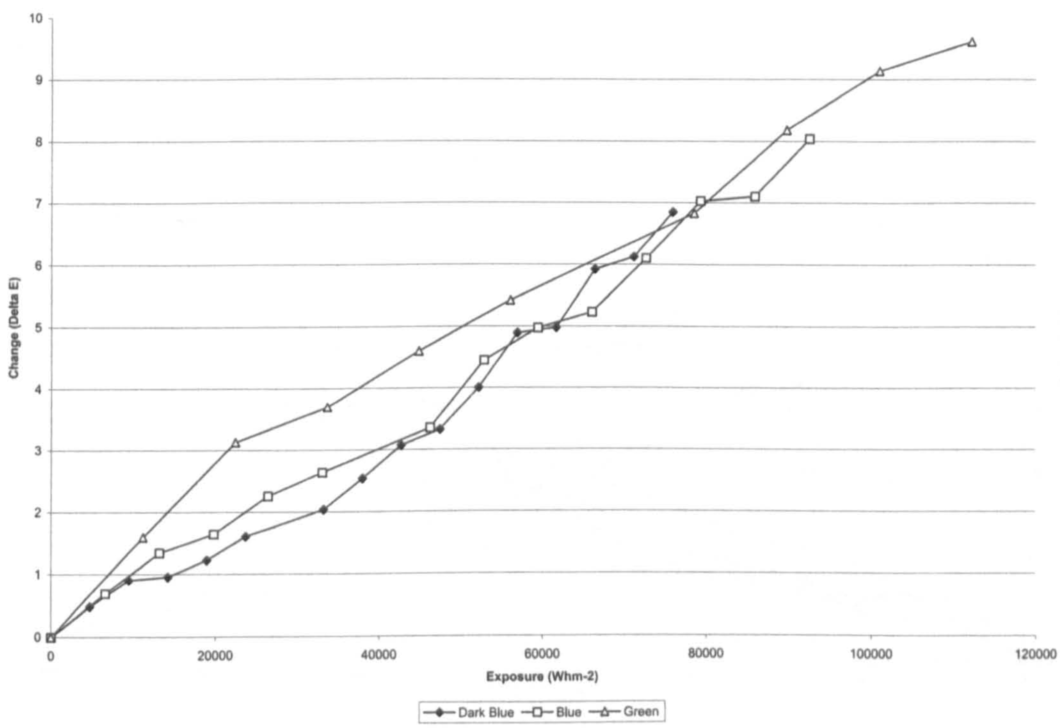
J.54 Plot showing the change in ΔEab against exposure for the red ink patch from the Epson Pro 9000 ink set printed on the Somerset Velvet paper (3.3), exposed to fluorescent light under the dichroic filters.



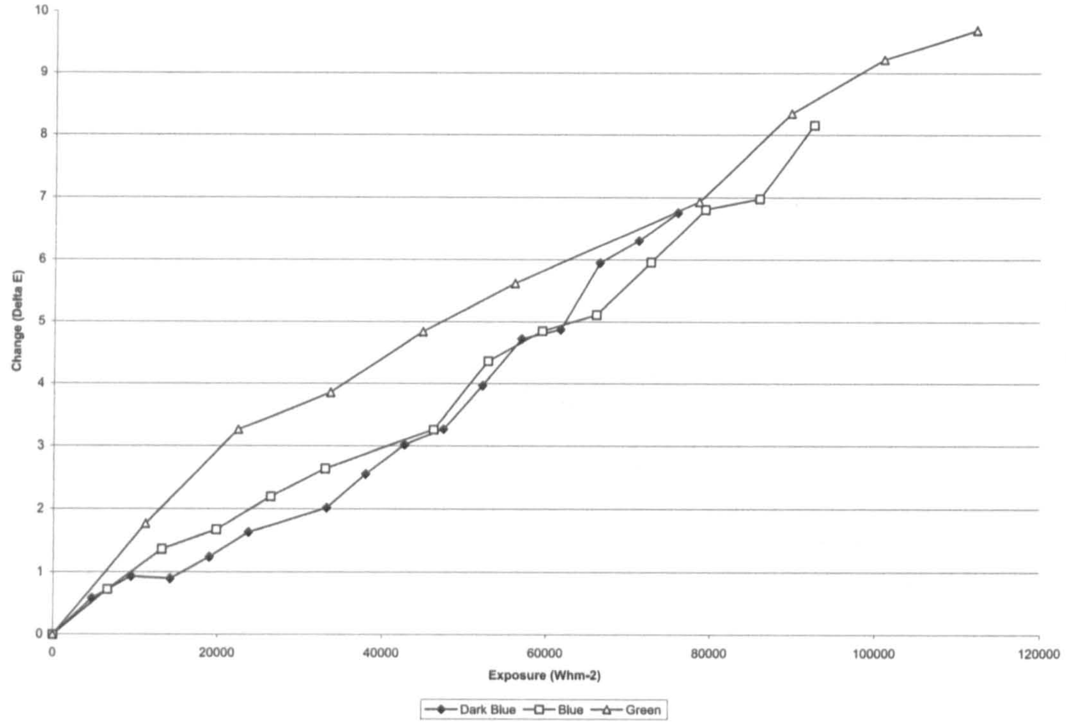
J.55 Plot showing the change in ΔEab against exposure for the green ink patch from the Epson Pro 9000 ink set printed on the Somerset Velvet paper (3.3), exposed to fluorescent light under the dichroic filters.



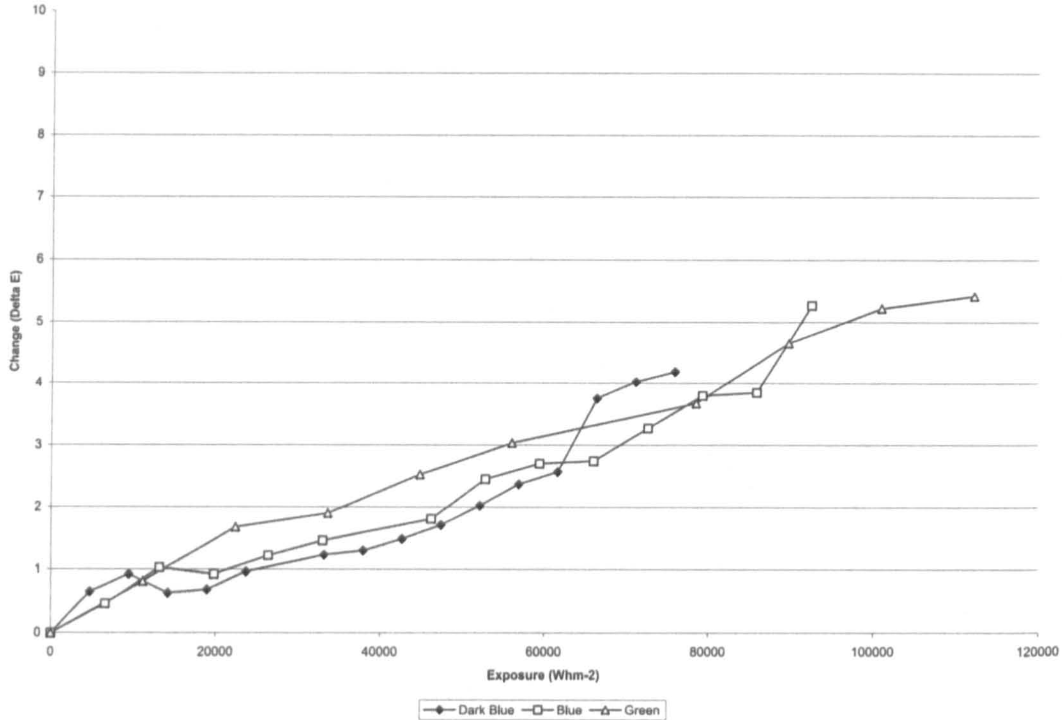
J.56 Plot showing the change in ΔEab against exposure for the 25 % CMY ink patch from the Epson Pro 9000 ink set printed on the Somerset Velvet paper (3.3), exposed to fluorescent light under the dichroic filters.



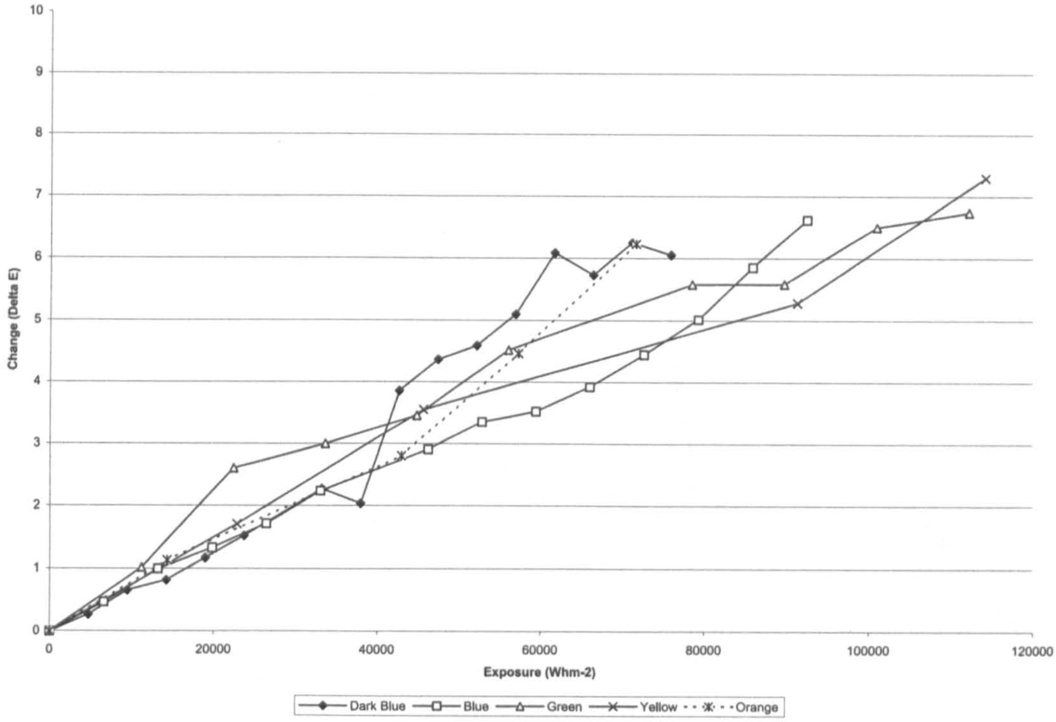
J.57 Plot showing the change in ΔEab against exposure for the 50 % CMY ink patch from the Epson Pro 9000 ink set printed on the Somerset Velvet paper (3.3), exposed to fluorescent light under the dichroic filters.



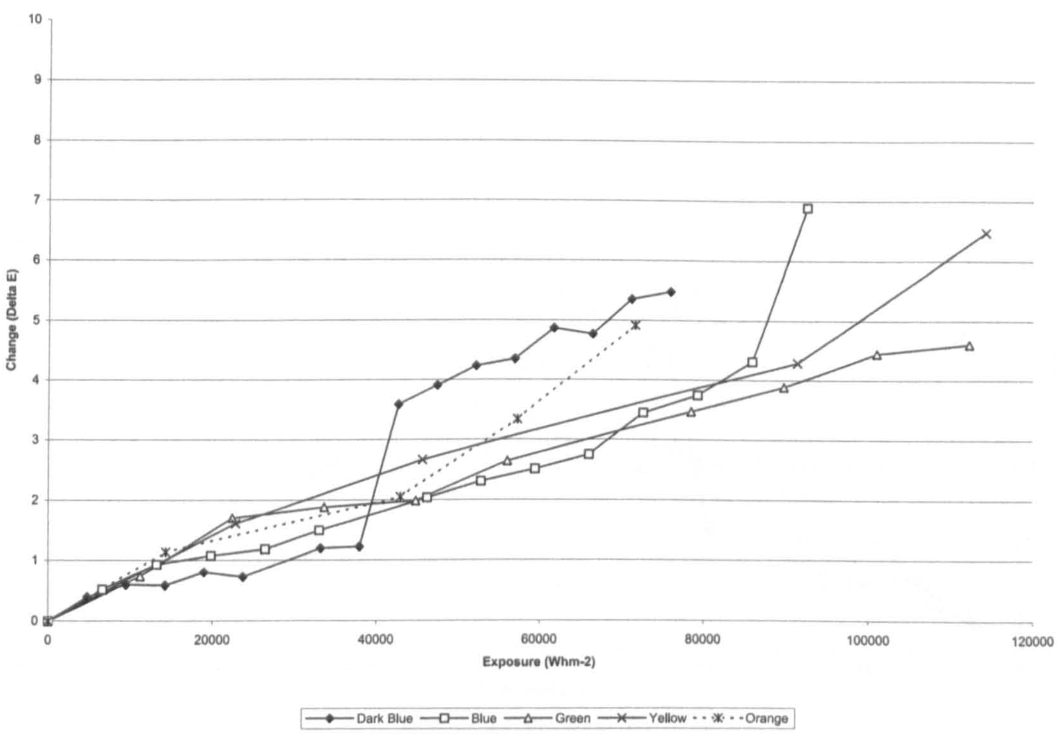
J.58 Plot showing the change in ΔEab against exposure for the 25 % CMYK ink patch from the Epson Pro 9000 ink set printed on the Somerset Velvet paper (3.3), exposed to fluorescent light under the dichroic filters.



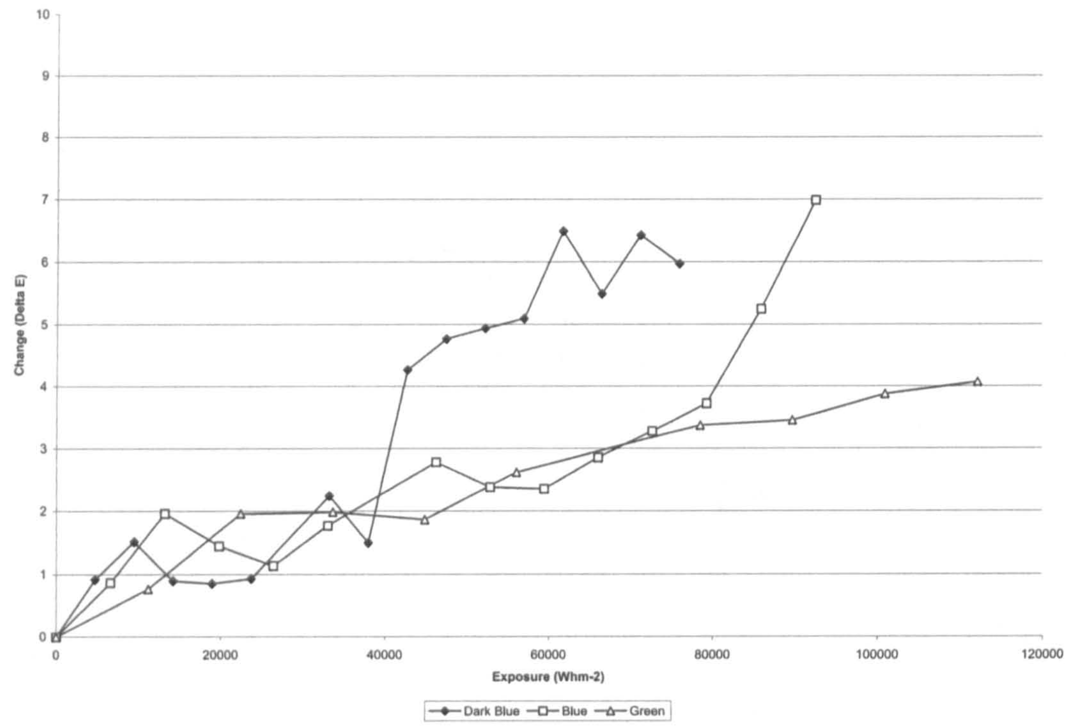
J.59 Plot showing the change in ΔEab against exposure for the 50 % CMYK ink patch from the Epson Pro 9000 ink set printed on the Somerset Velvet paper (3.3), exposed to fluorescent light under the dichroic filters.



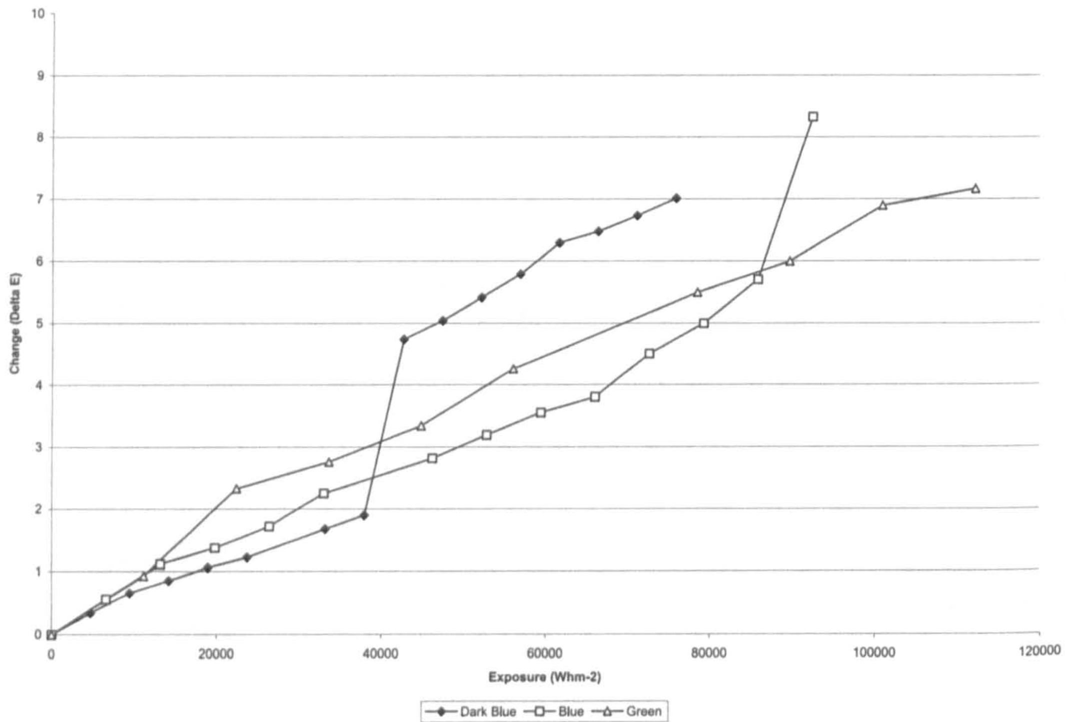
J.60 Plot showing the change in ΔEab against exposure for the cyan ink patch from the Epson Pro 9000 ink set printed on the Whatman watercolour paper (3.4), exposed to fluorescent light under the dichroic filters.



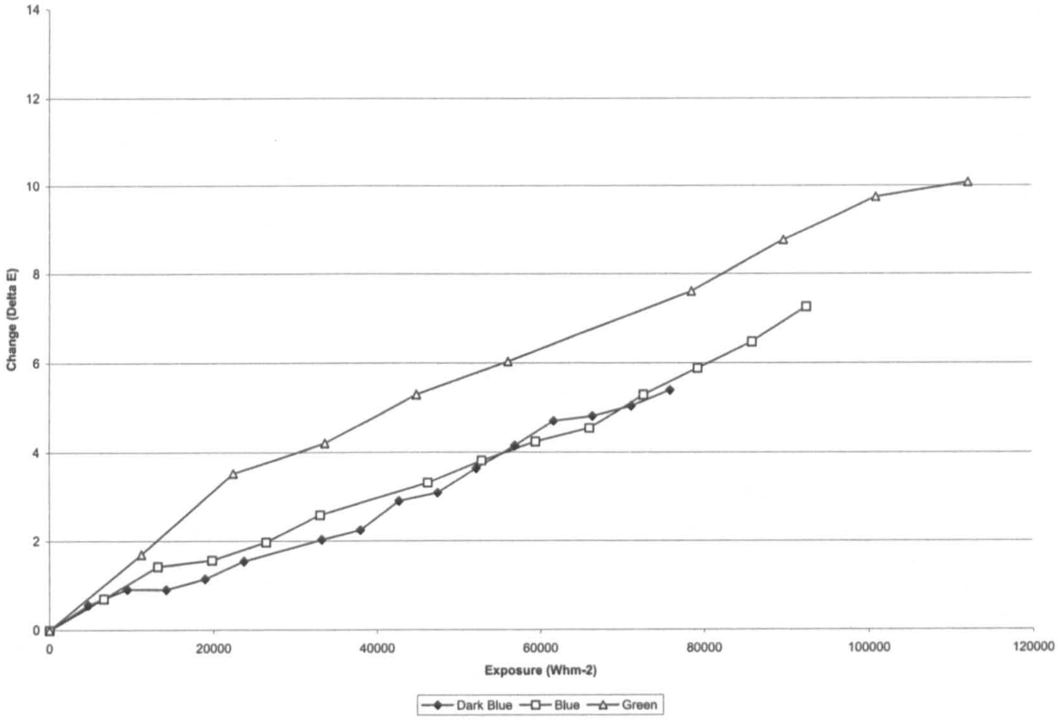
J.61 Plot showing the change in ΔEab against exposure for the magenta ink patch from the Epson Pro 9000 ink set printed on the Whatman watercolour paper (3.4), exposed to fluorescent light under the dichroic filters.



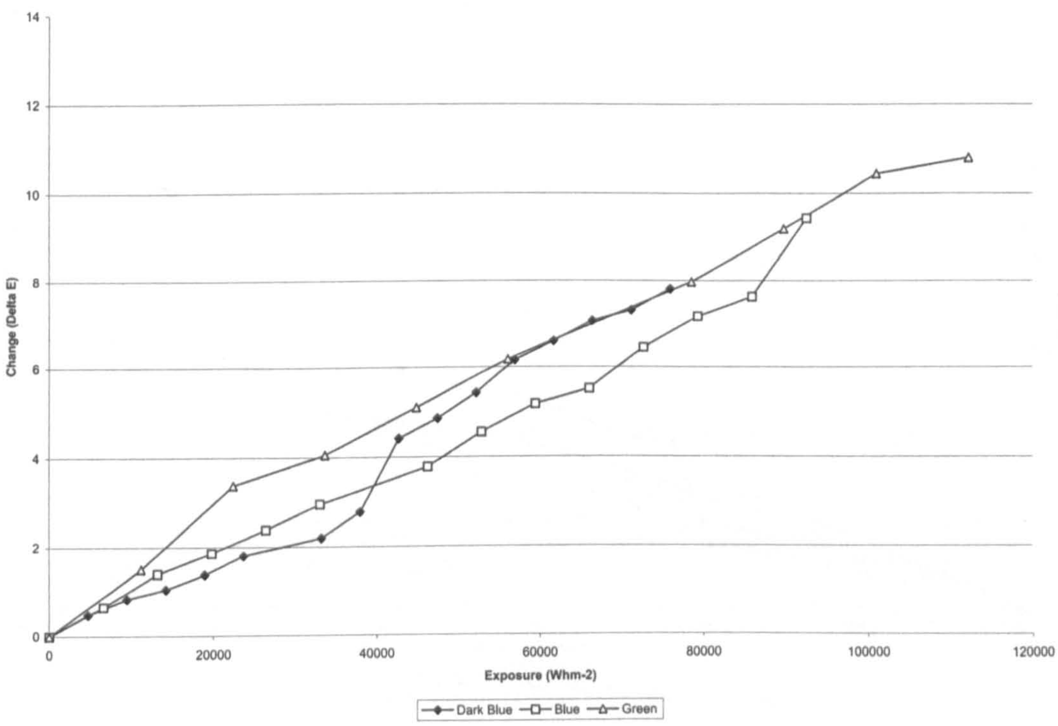
J.62 Plot showing the change in ΔEab against exposure for the red ink patch from the Epson Pro 9000 ink set printed on the Whatman watercolour paper (3.4), exposed to fluorescent light under the dichroic filters.



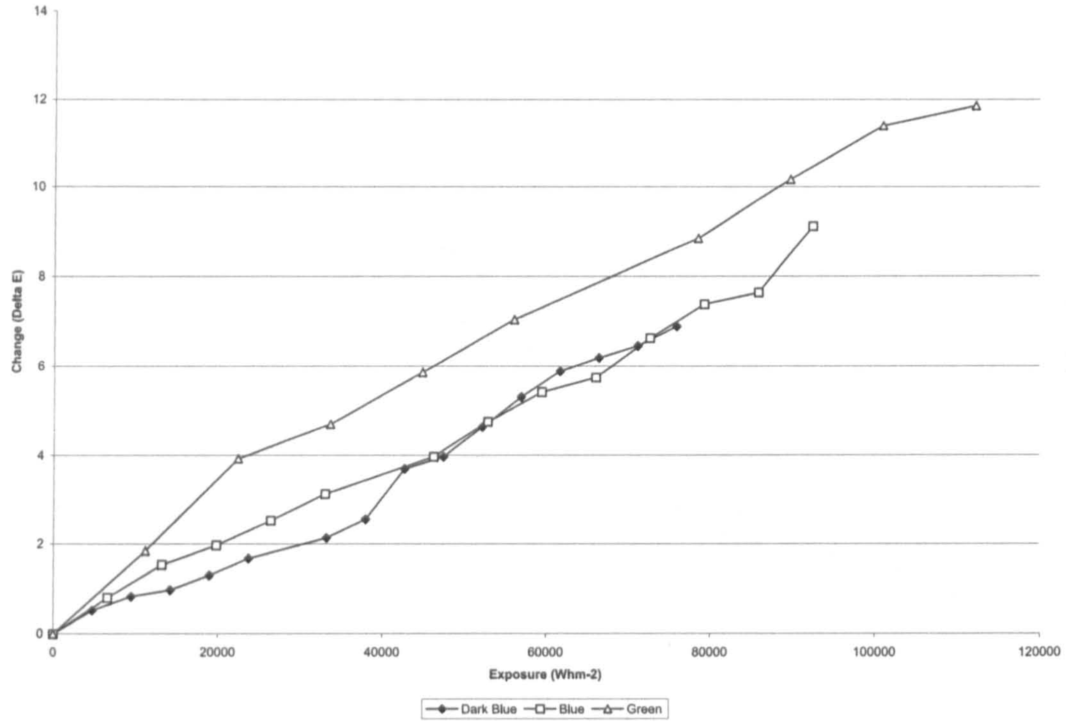
J.63 Plot showing the change in ΔEab against exposure for the blue ink patch from the Epson Pro 9000 ink set printed on the Whatman watercolour paper (3.4), exposed to fluorescent light under the dichroic filters.



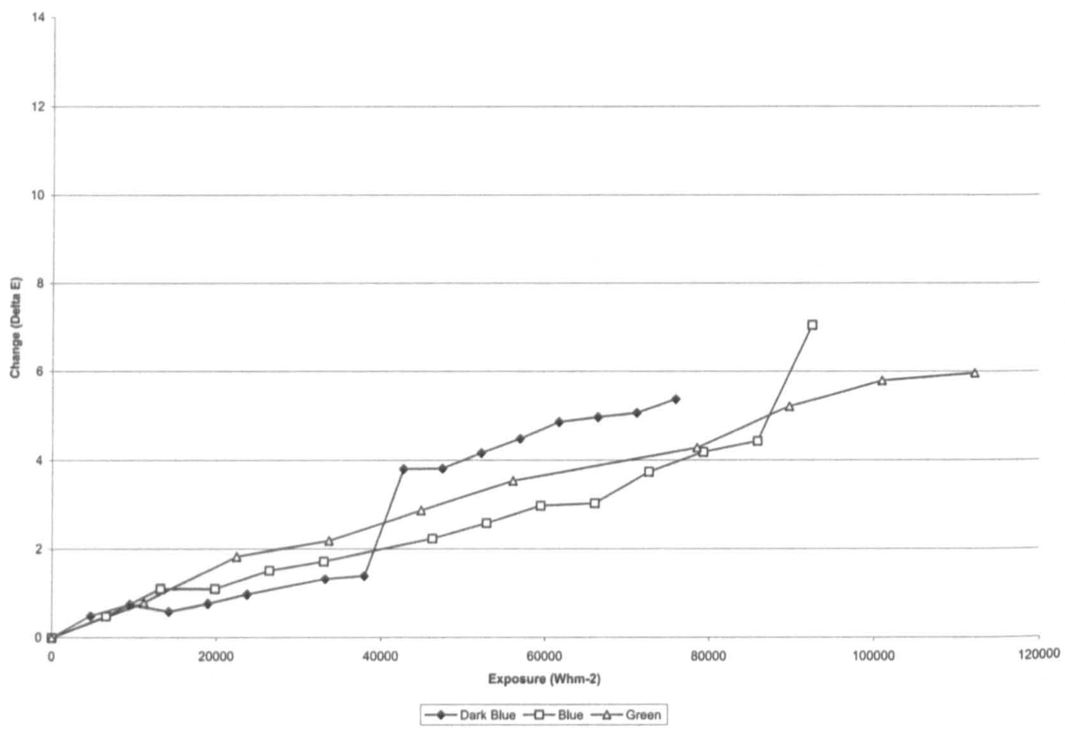
J.64 Plot showing the change in ΔEab against exposure for the 25 % CMY ink patch from the Epson Pro 9000 ink set printed on the Whatman watercolour paper (3.4), exposed to fluorescent light under the dichroic filters.



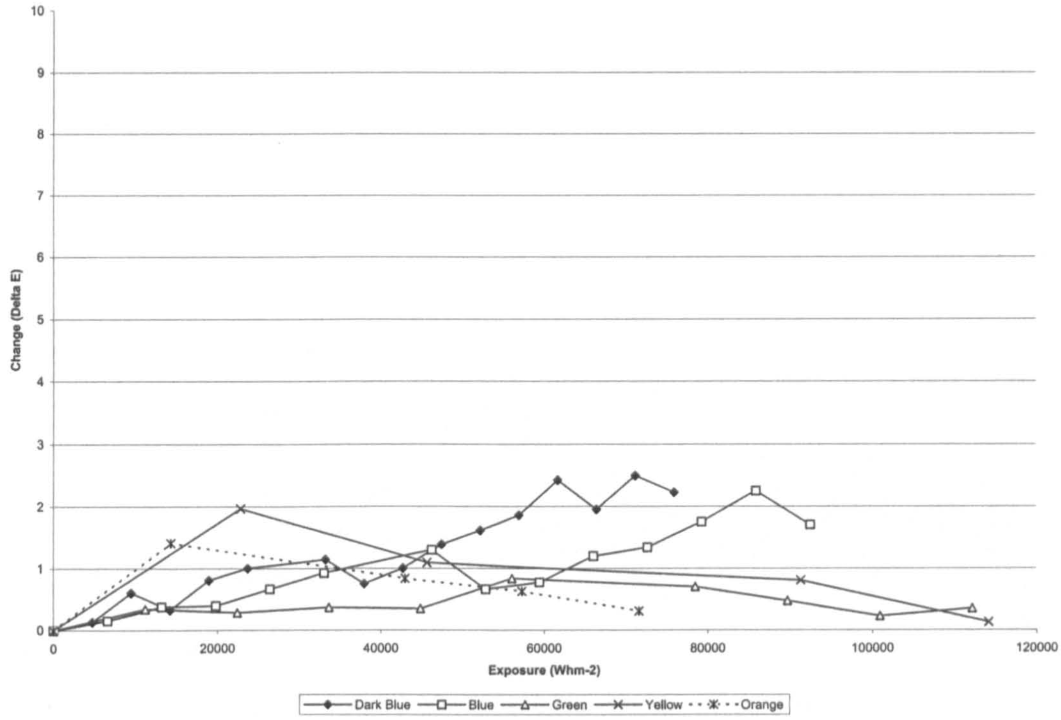
J.65 Plot showing the change in ΔEab against exposure for the 50 % CMY ink patch from the Epson Pro 9000 ink set printed on the Whatman watercolour paper (3.4), exposed to fluorescent light under the dichroic filters.



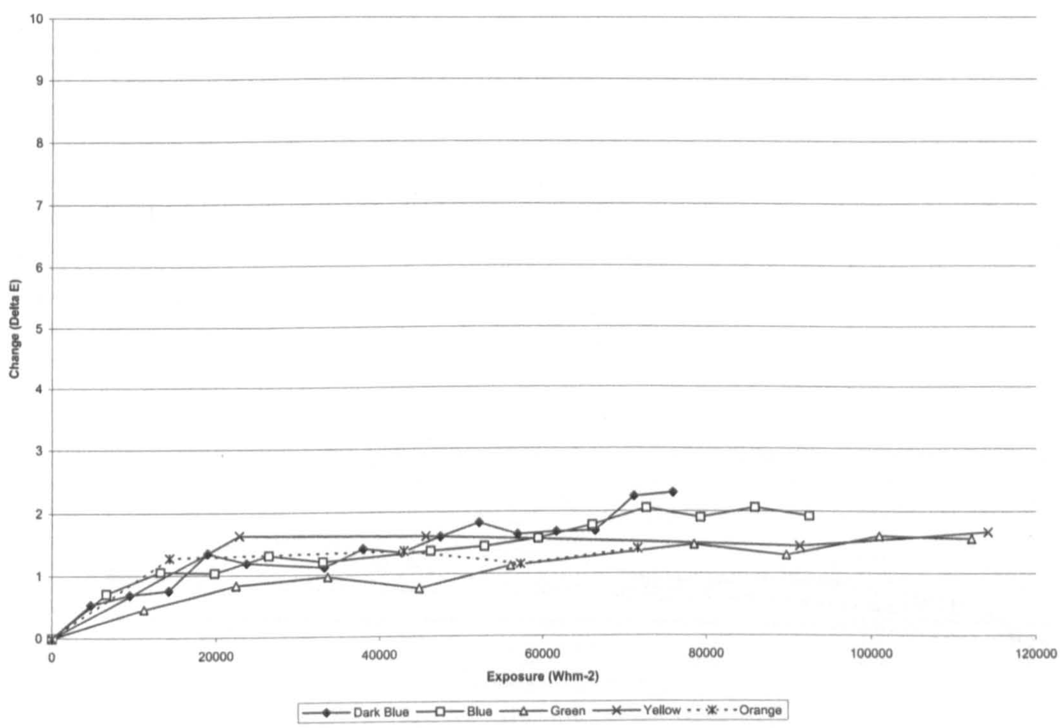
J.66 Plot showing the change in ΔEab against exposure for the 25 % CMYK ink patch from the Epson Pro 9000 ink set printed on the Whatman watercolour paper (3.4), exposed to fluorescent light under the dichroic filters.



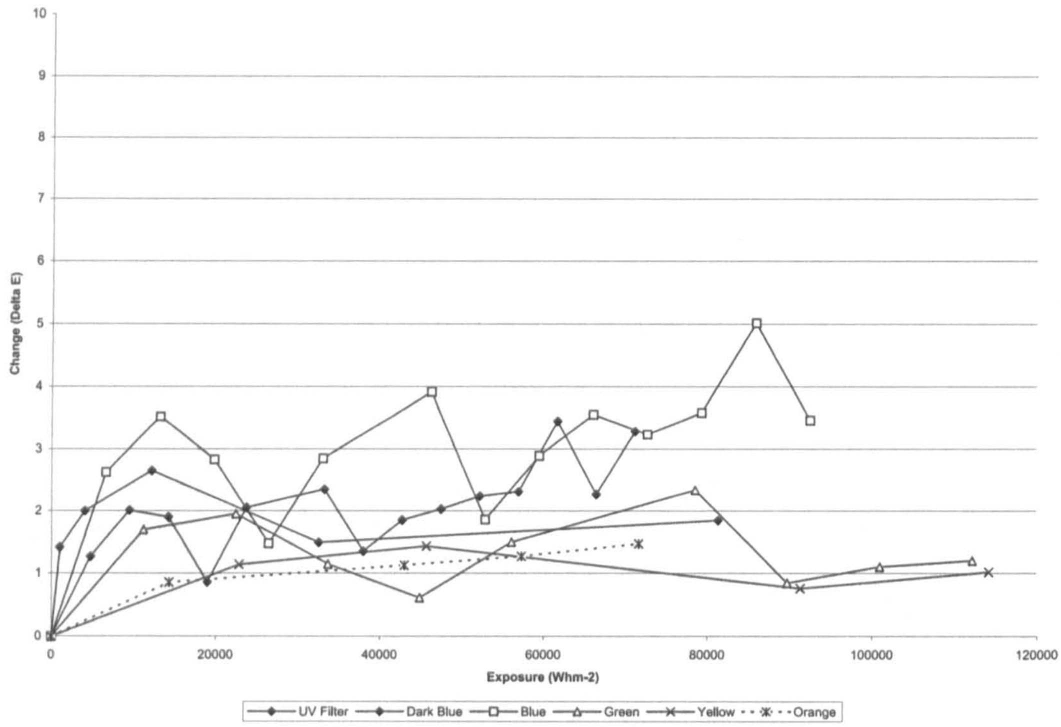
J.67 Plot showing the change in ΔEab against exposure for the 50 % CMYK ink patch from the Epson Pro 9000 ink set printed on the Whatman watercolour paper (3.4), exposed to fluorescent light under the dichroic filters.



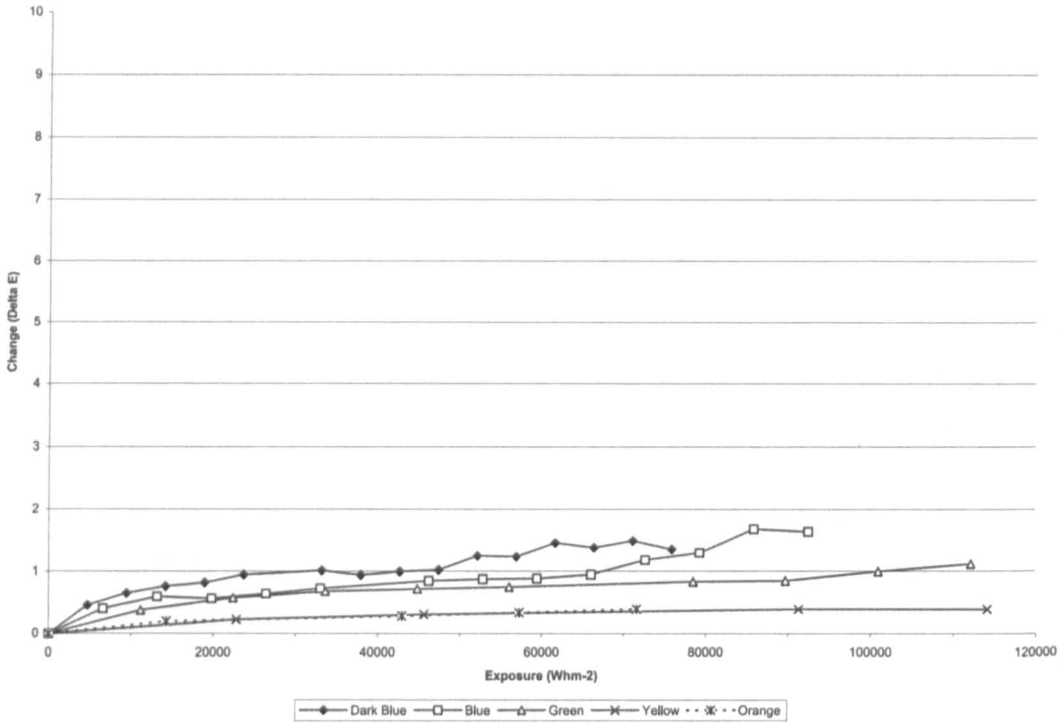
J.68 Plot showing the change in ΔEab against exposure for the cyan ink patch from the Epson Pro 9000 ink set printed on the Epson Presentation Matt paper (3.5), exposed to fluorescent light under the dichroic filters.



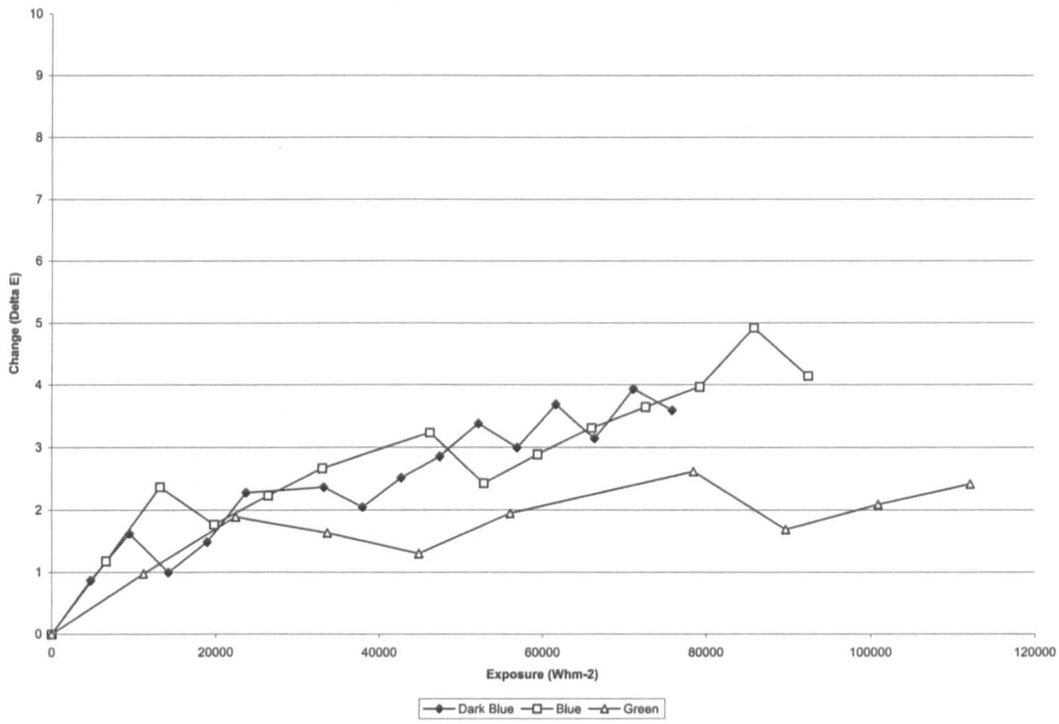
J.69 Plot showing the change in ΔEab against exposure for the magenta ink patch from the Epson Pro 9000 ink set printed on the Epson Presentation Matt paper (3.5), exposed to fluorescent light under the dichroic filters.



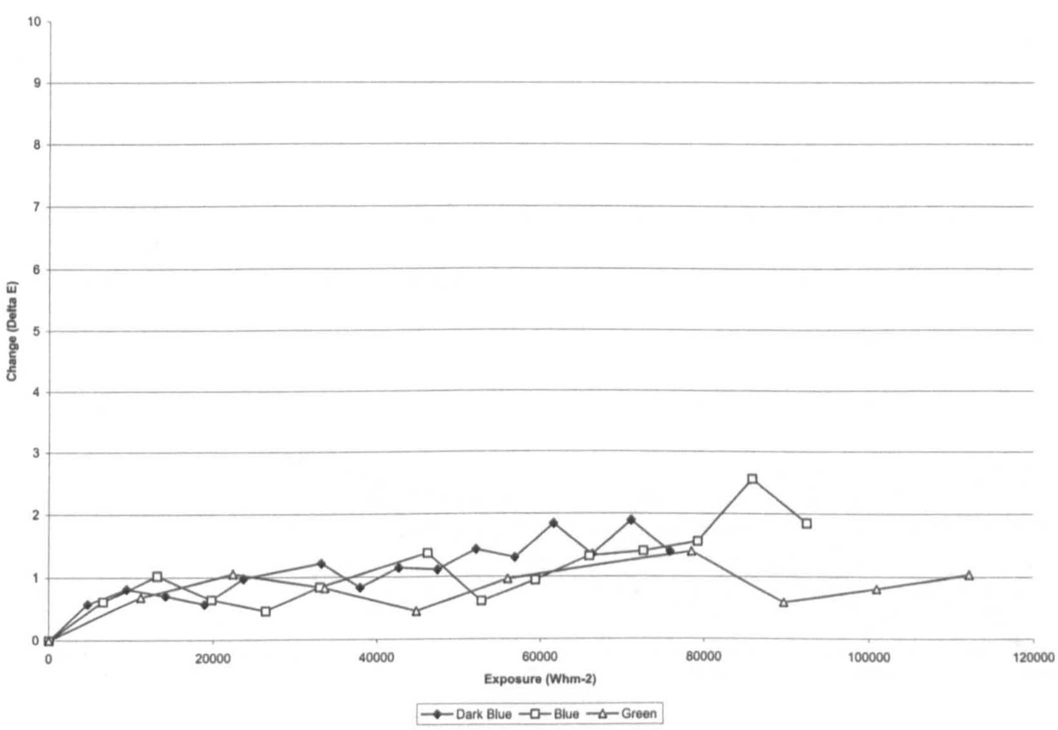
J.70 Plot showing the change in ΔEab against exposure for the yellow ink patch from the Epson Pro 9000 ink set printed on the Epson Presentation Matt paper (3.5), exposed to fluorescent light under the dichroic filters.



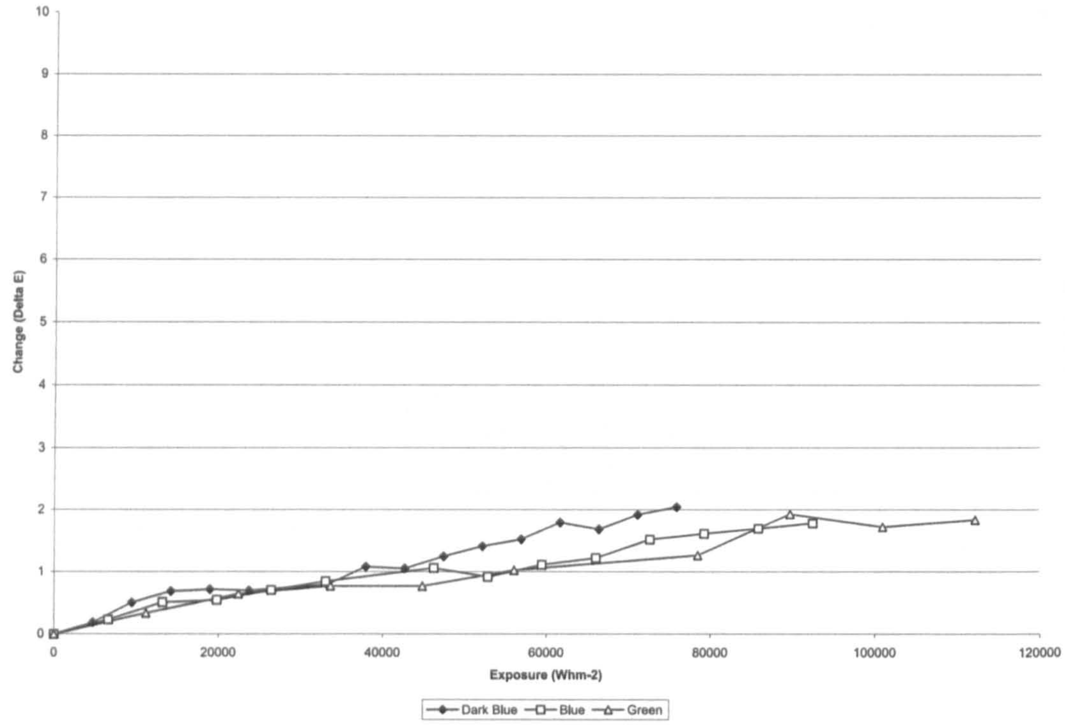
J.71 Plot showing the change in ΔEab against exposure for the black ink patch from the Epson Pro 9000 ink set printed on the Epson Presentation Matt paper (3.5), exposed to fluorescent light under the dichroic filters.



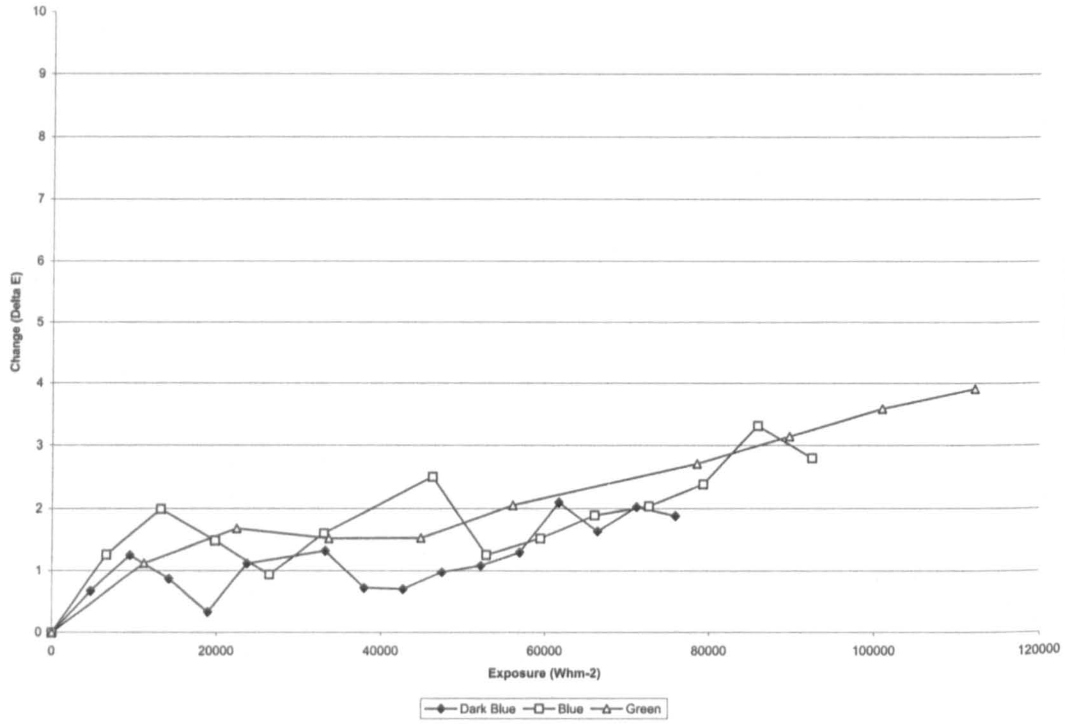
J.72 Plot showing the change in ΔEab against exposure for the red ink patch from the Epson Pro 9000 ink set printed on the Epson Presentation Matt paper (3.5), exposed to fluorescent light under the dichroic filters.



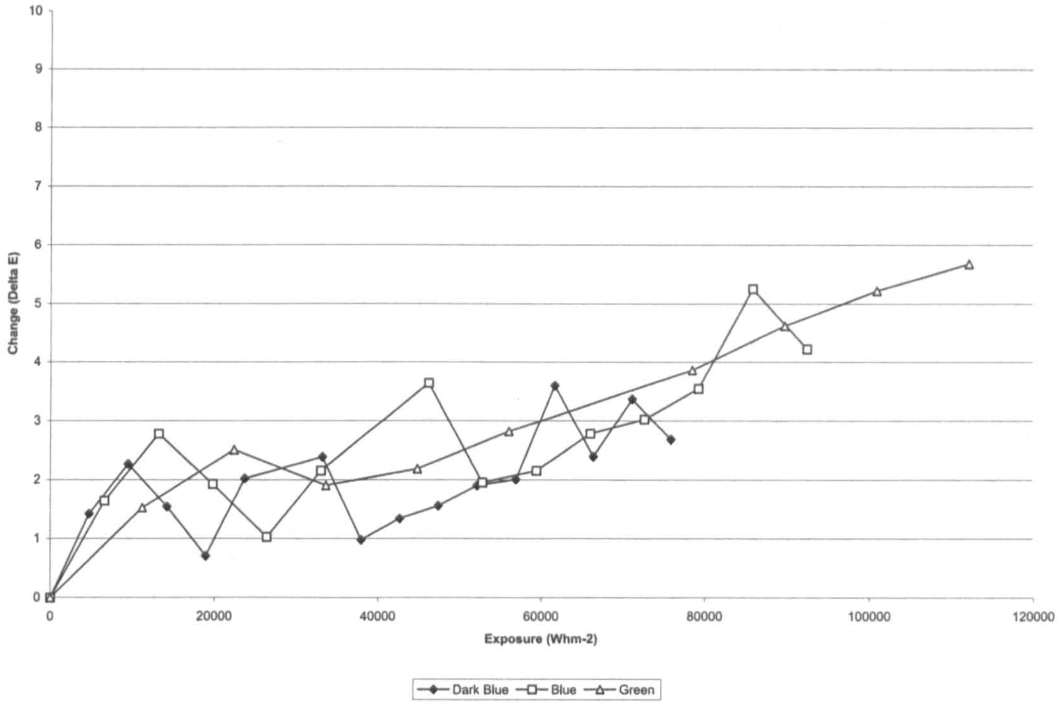
J.73 Plot showing the change in ΔEab against exposure for the green ink patch from the Epson Pro 9000 ink set printed on the Epson Presentation Matt paper (3.5), exposed to fluorescent light under the dichroic filters.



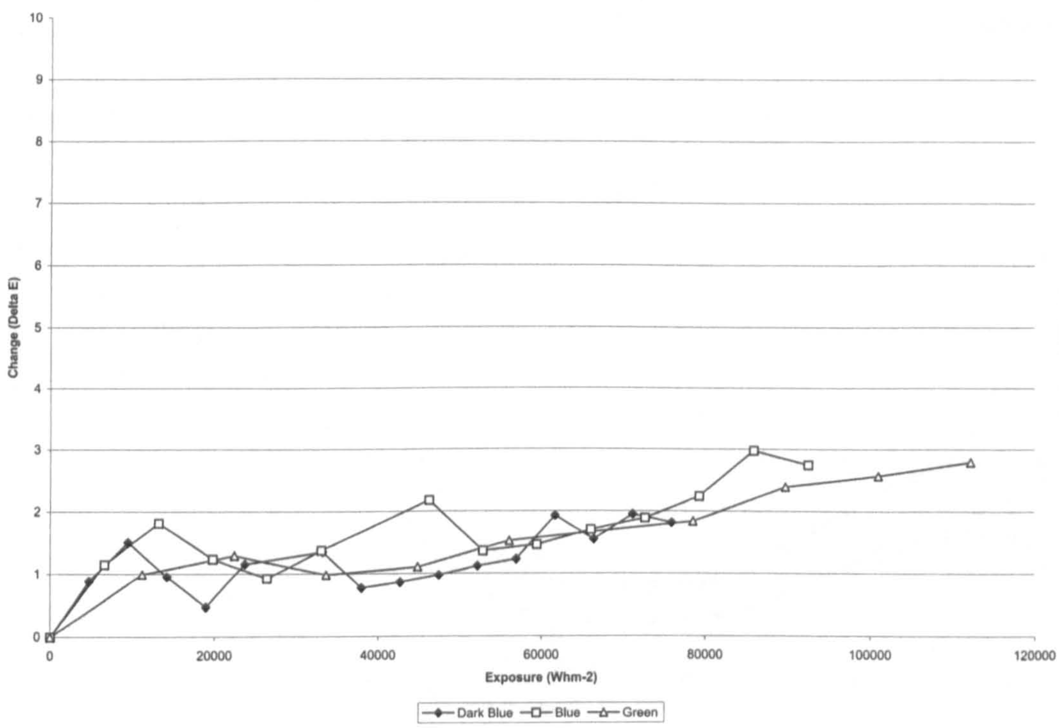
J.74 Plot showing the change in ΔEab against exposure for the blue ink patch from the Epson Pro 9000 ink set printed on the Epson Presentation Matt paper (3.5), exposed to fluorescent light under the dichroic filters.



J.75 Plot showing the change in ΔEab against exposure for the 25 % CMY ink patch from the Epson Pro 9000 ink set printed on the Epson Presentation Matt paper (3.5), exposed to fluorescent light under the dichroic filters.

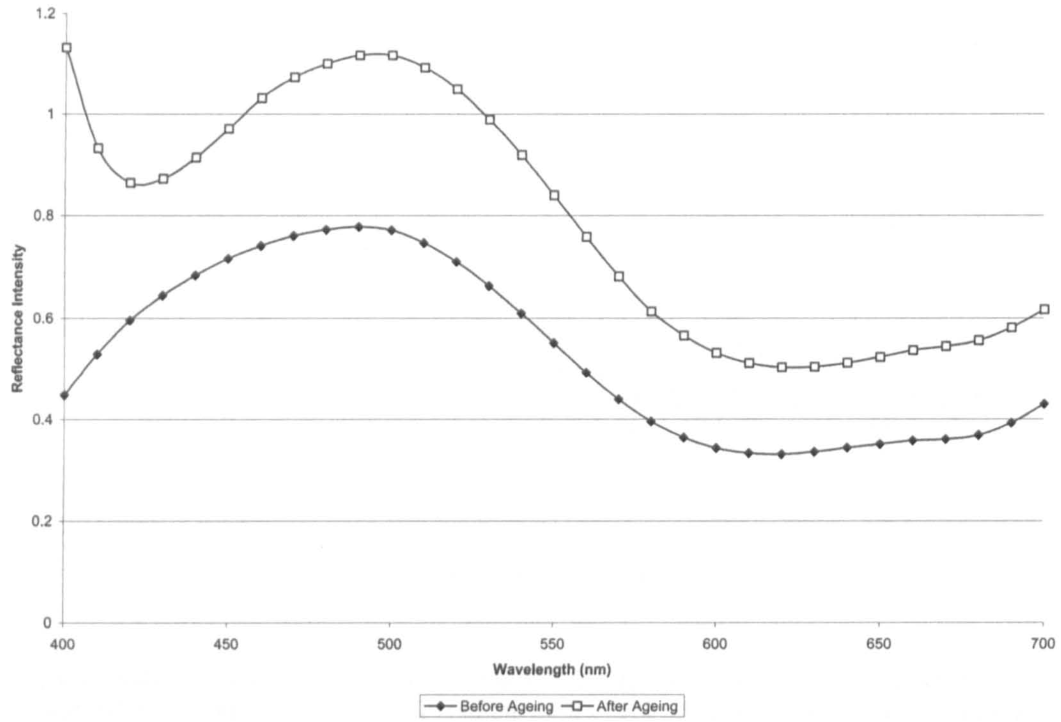


J.76 Plot showing the change in ΔEab against exposure for the 50 % CMY ink patch from the Epson Pro 9000 ink set printed on the Epson Presentation Matt paper (3.5), exposed to fluorescent light under the dichroic filters.

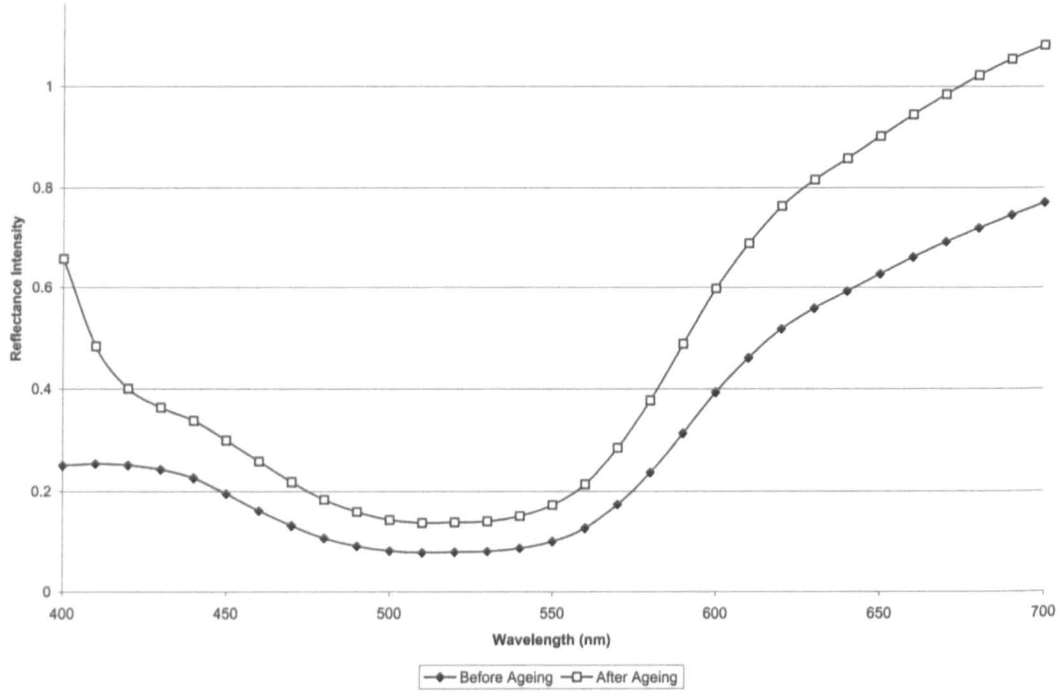


J.77 Plot showing the change in ΔEab against exposure for the 25 % CMYK ink patch from the Epson Pro 9000 ink set printed on the Epson Presentation Matt paper (3.5), exposed to fluorescent light under the dichroic filters.

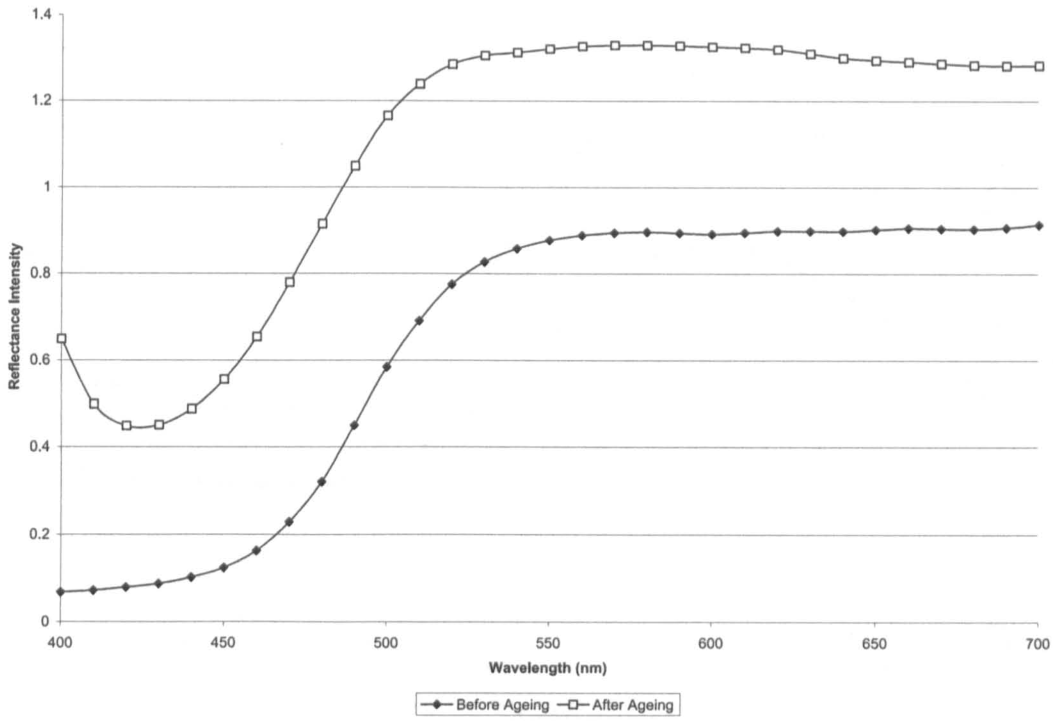
APPENDIX K - Spectral reflectance curves for the print samples exposed to natural daylight



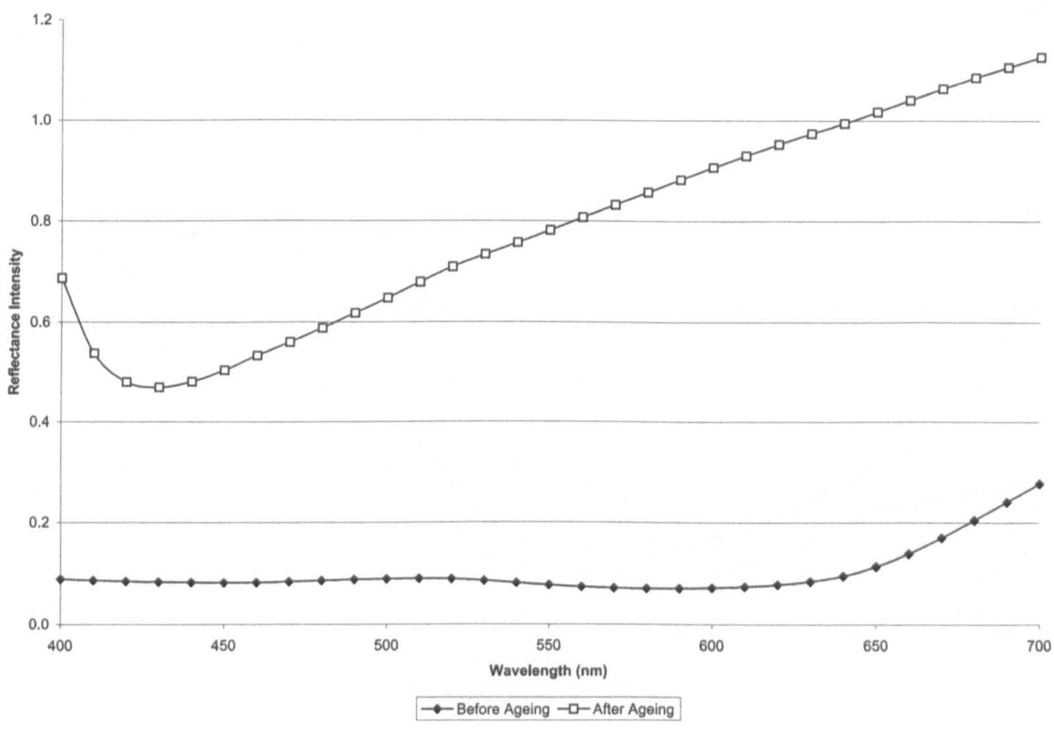
K.1 Plot showing the change in reflectance spectra of the cyan ink from the Iris Morgan FA ink set printed on Somerset Velvet paper (1.1) after exposure to daylight for 50,863 klux hours unfiltered.



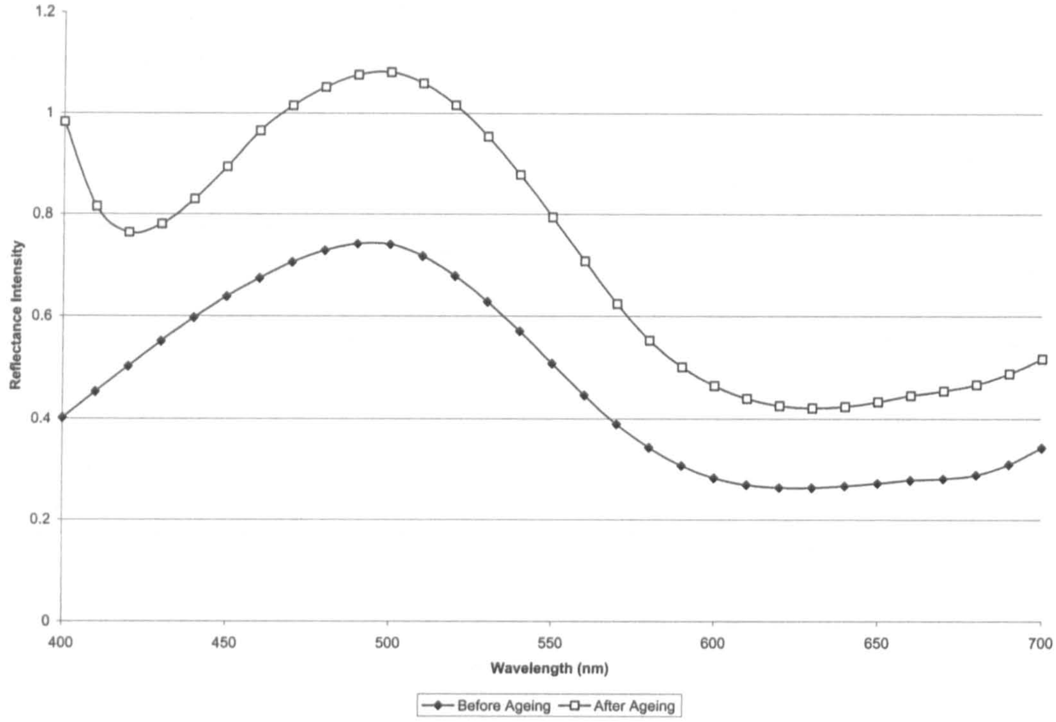
K.2 Plot showing the change in reflectance spectra of the magenta ink from the Iris Morgan FA ink set printed on Somerset Velvet paper (1.1) after exposure to daylight for 50,863 klux hours unfiltered.



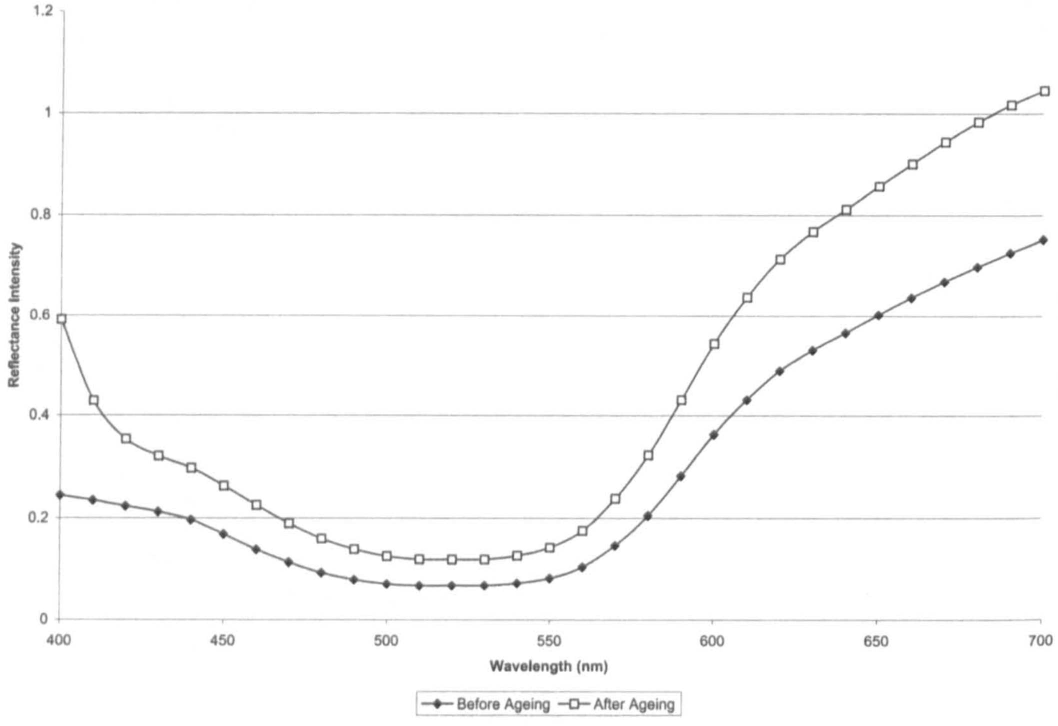
K.3 Plot showing the change in reflectance spectra of the yellow ink from the Iris Morgan FA ink set printed on Somerset Velvet paper (1.1) after exposure to daylight for 50,863 klux hours unfiltered.



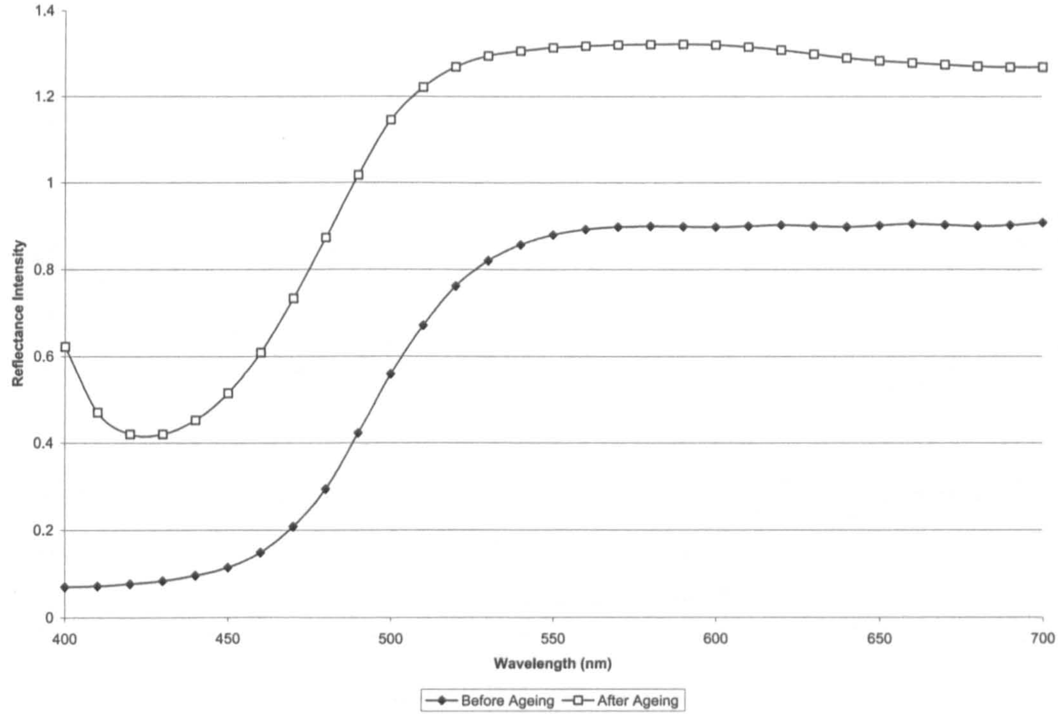
K.4 Plot showing the change in reflectance spectra of the black ink from the Iris Morgan FA ink set printed on Somerset Velvet paper (1.1) after exposure to daylight for 50,863 klux hours unfiltered.



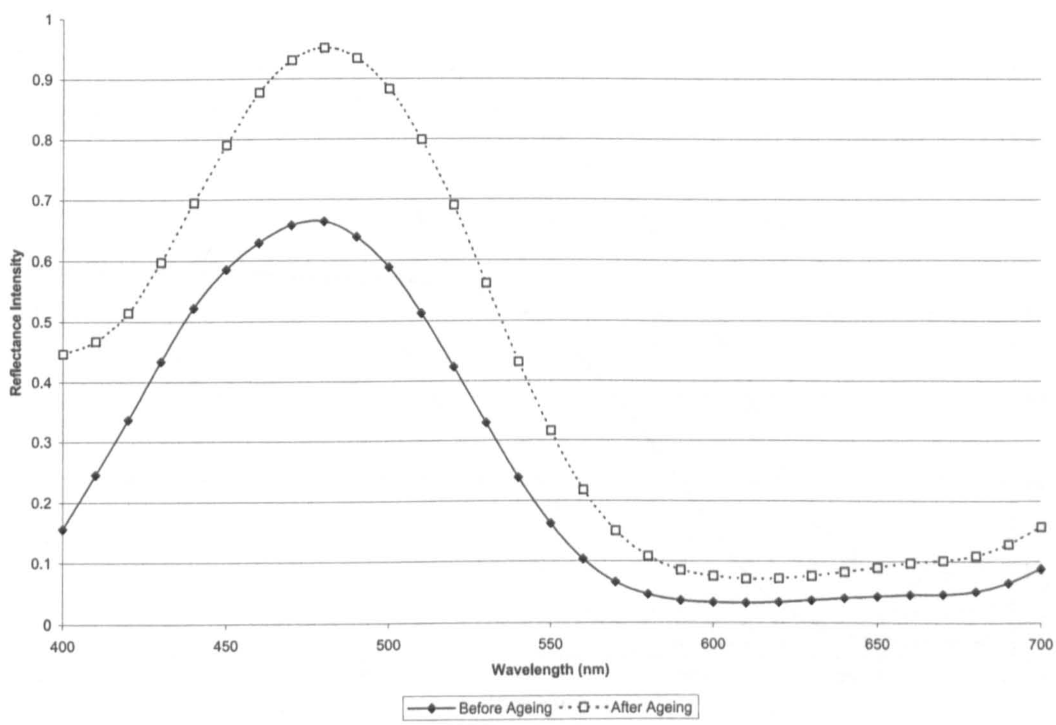
K.5 Plot showing the change in reflectance spectra of the cyan ink from the Iris Morgan FA ink set printed on Whatman paper (1.2) after exposure to daylight for 50,863 klux hours unfiltered.



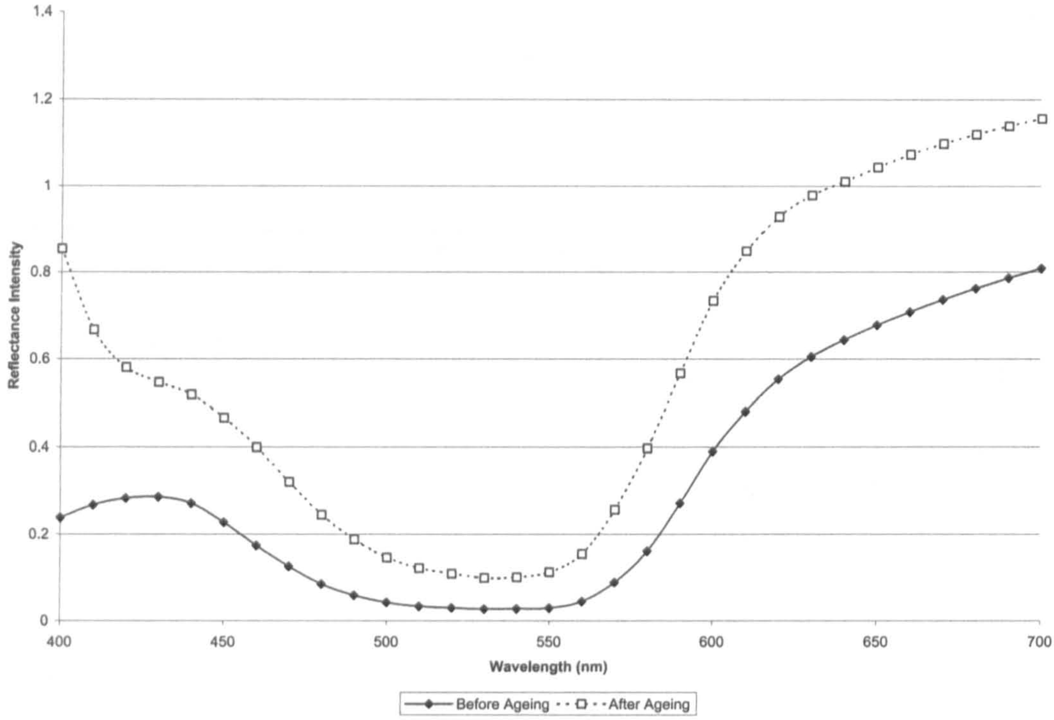
K.6 Plot showing the change in reflectance spectra of the magenta ink from the Iris Morgan FA ink set printed on Whatman paper (1.2) after exposure to daylight for 50,863 klux hours unfiltered.



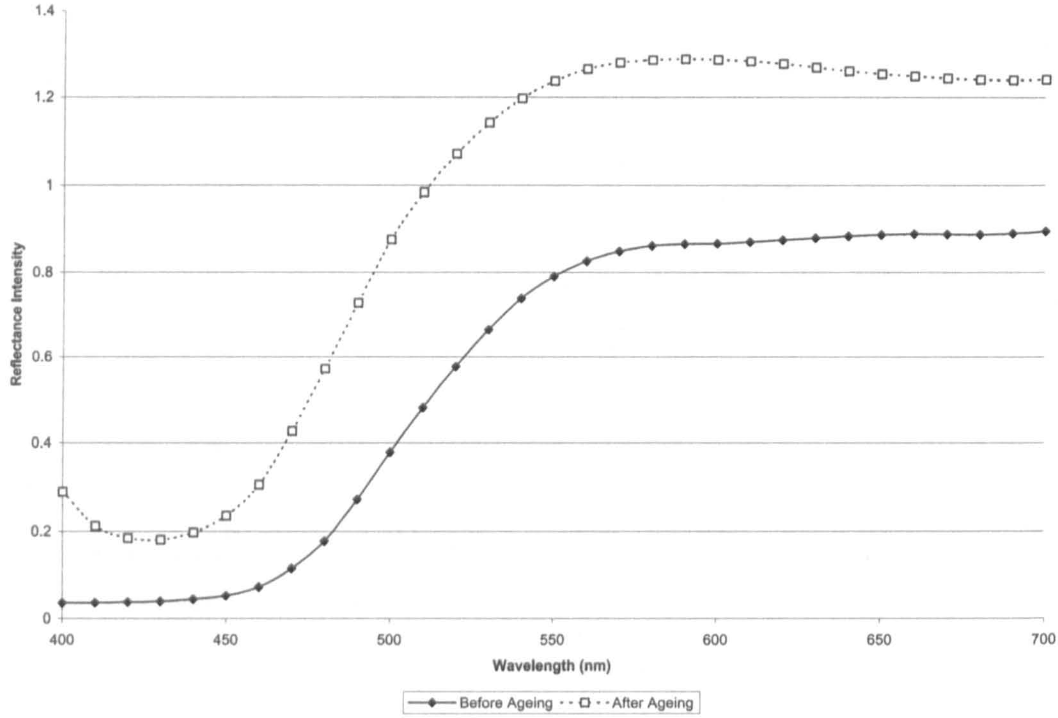
K.7 Plot showing the change in reflectance spectra of the yellow ink from the Iris Morgan FA ink set printed on Whatman paper (1.2) after exposure to daylight for 50,863 klux hours unfiltered.



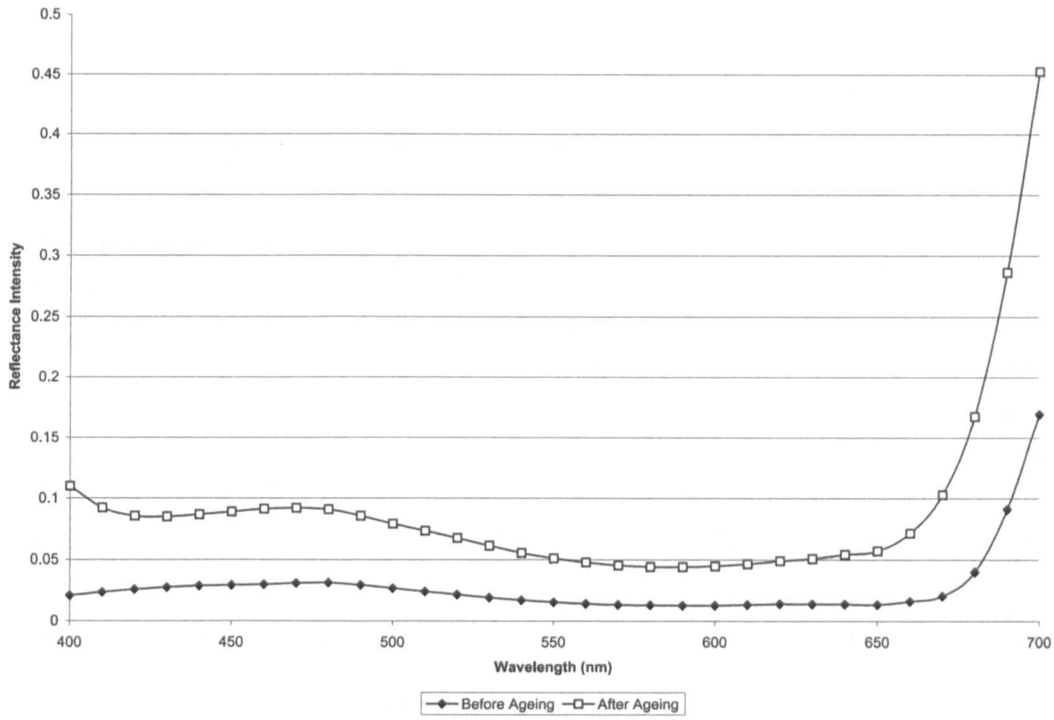
K.8 Plot showing the change in reflectance spectra of the cyan ink from the Lysonic ink set printed on Lyson Soft Fine Art paper (2.1) after exposure to daylight for 50,863 klux hours unfiltered.



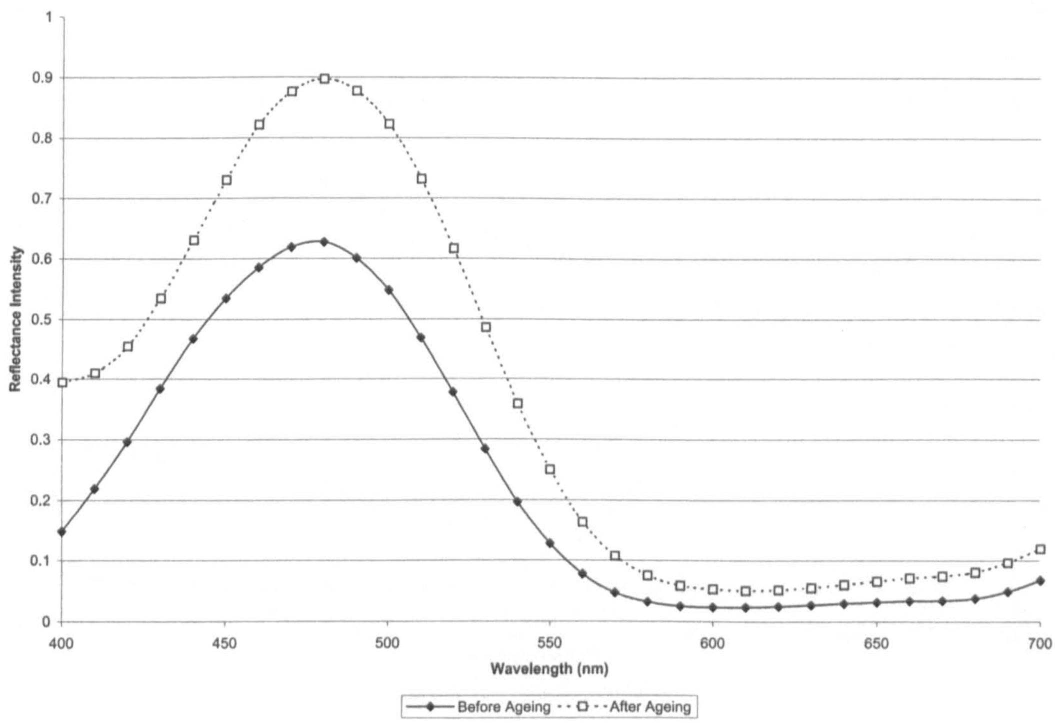
K.9 Plot showing the change in reflectance spectra of the magenta ink from the Lysonic ink set printed on Lyson Soft Fine Art paper (2.1) after exposure to daylight for 50,863 klux hours unfiltered.



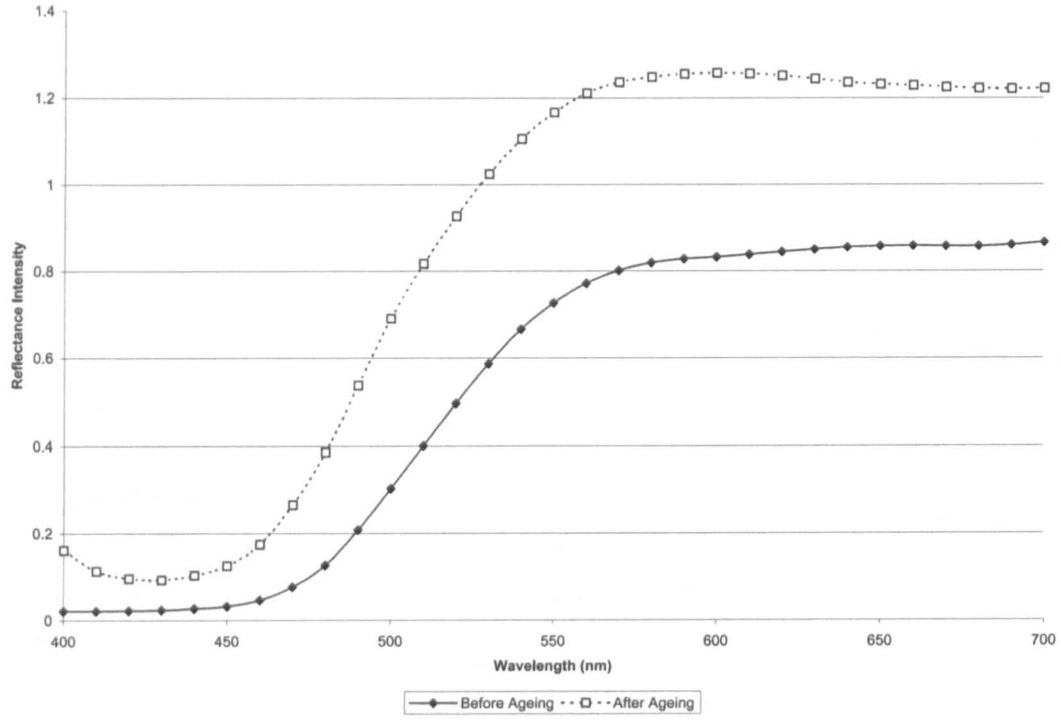
K.10 Plot showing the change in reflectance spectra of the yellow ink from the Lysonic ink set printed on Lyson Soft Fine Art paper (2.1) after exposure to daylight for 50,863 klux hours unfiltered.



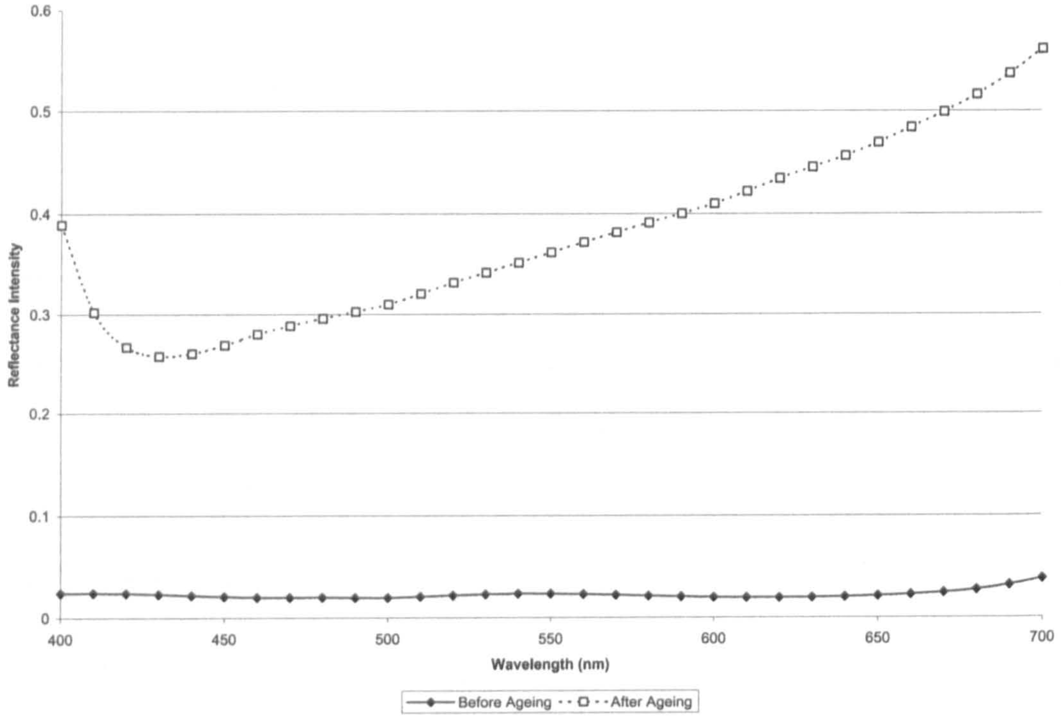
K.11 Plot showing the change in reflectance spectra of the black ink from the Lysonic ink set printed on Lyson Soft Fine Art paper (2.1) after exposure to daylight for 50,863 klux hours unfiltered.



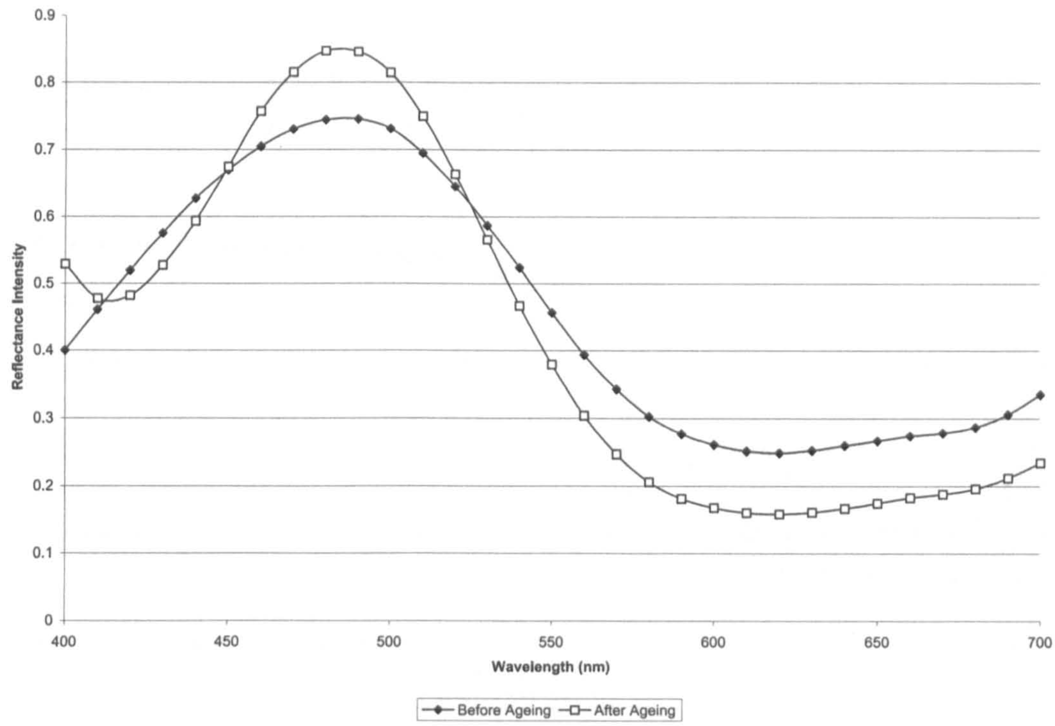
K.12 Plot showing the change in reflectance spectra of the cyan ink from the Fotonic ink set printed on Lyson Rough Fine Art paper (2.2) after exposure to daylight for 50,863 klux hours unfiltered.



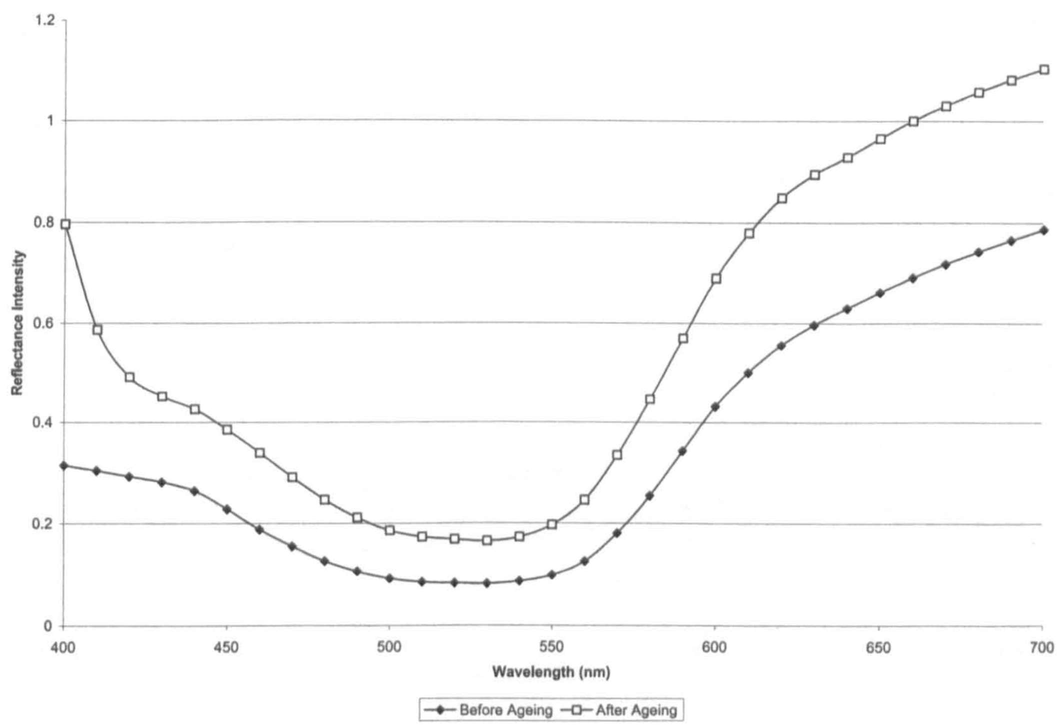
K.13 Plot showing the change in reflectance spectra of the yellow ink from the Fotonic ink set printed on Lyson Rough Fine Art paper (2.2) after exposure to daylight for 50,863 klux hours unfiltered.



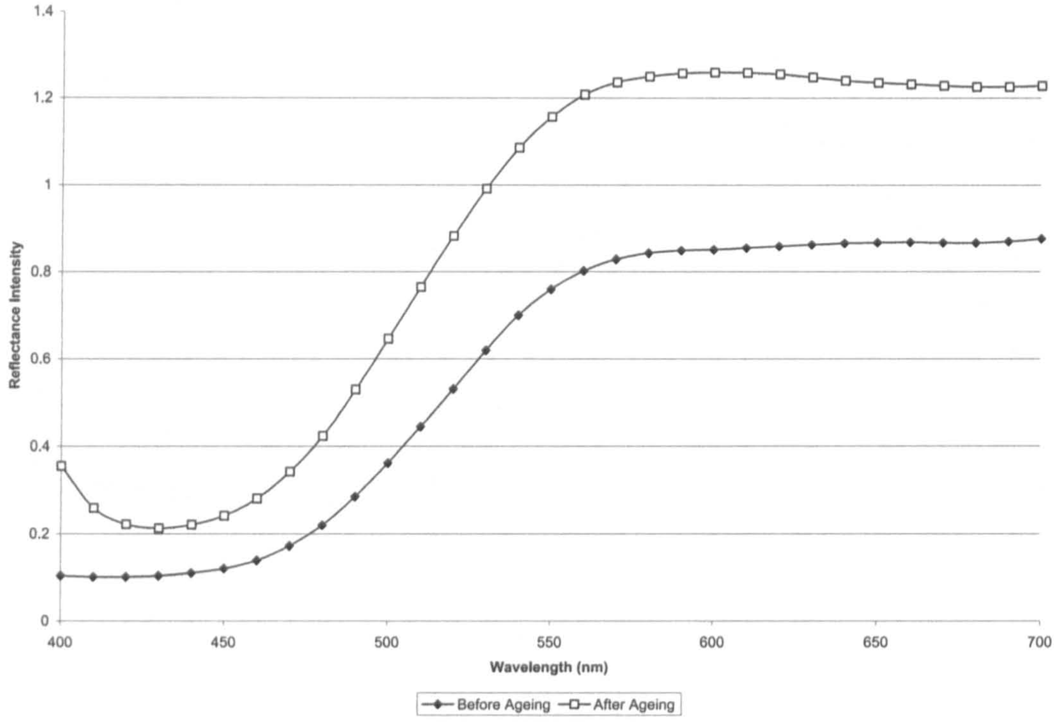
K.14 Plot showing the change in reflectance spectra of the black ink from the Fotonic ink set printed on Lyson Rough Fine Art paper (2.2) after exposure to daylight for 50,863 klux hours unfiltered.



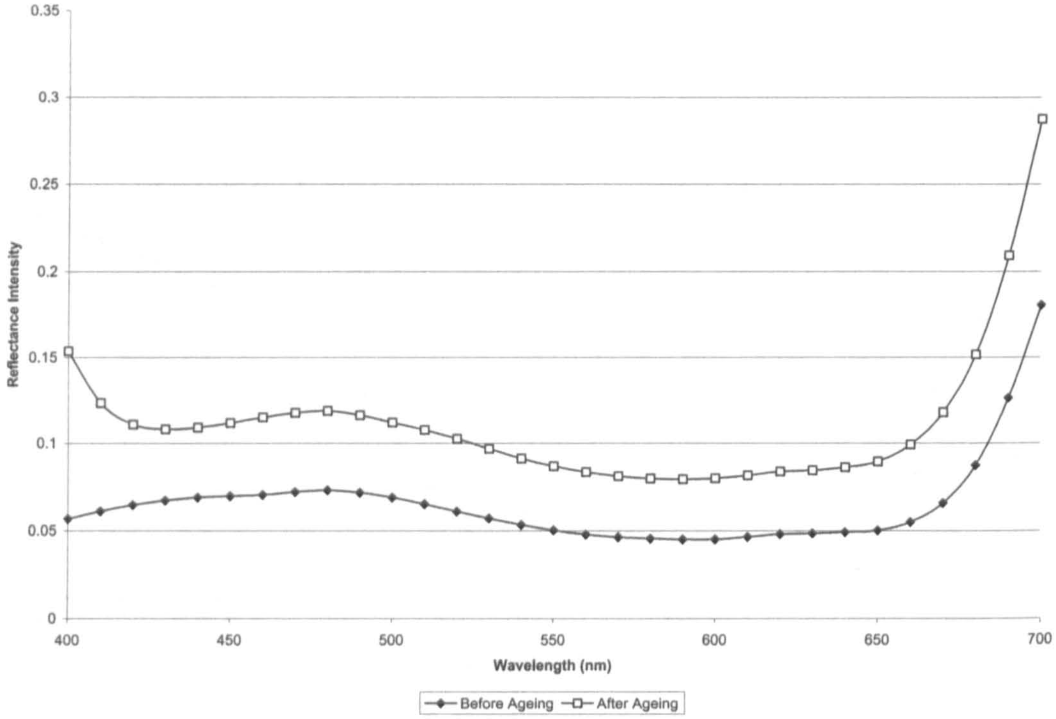
K.15 Plot showing the change in reflectance spectra of the cyan ink from the Lysonic ink set printed on Whatman watercolour paper (2.3) after exposure to daylight for 50,863 klux hours unfiltered.



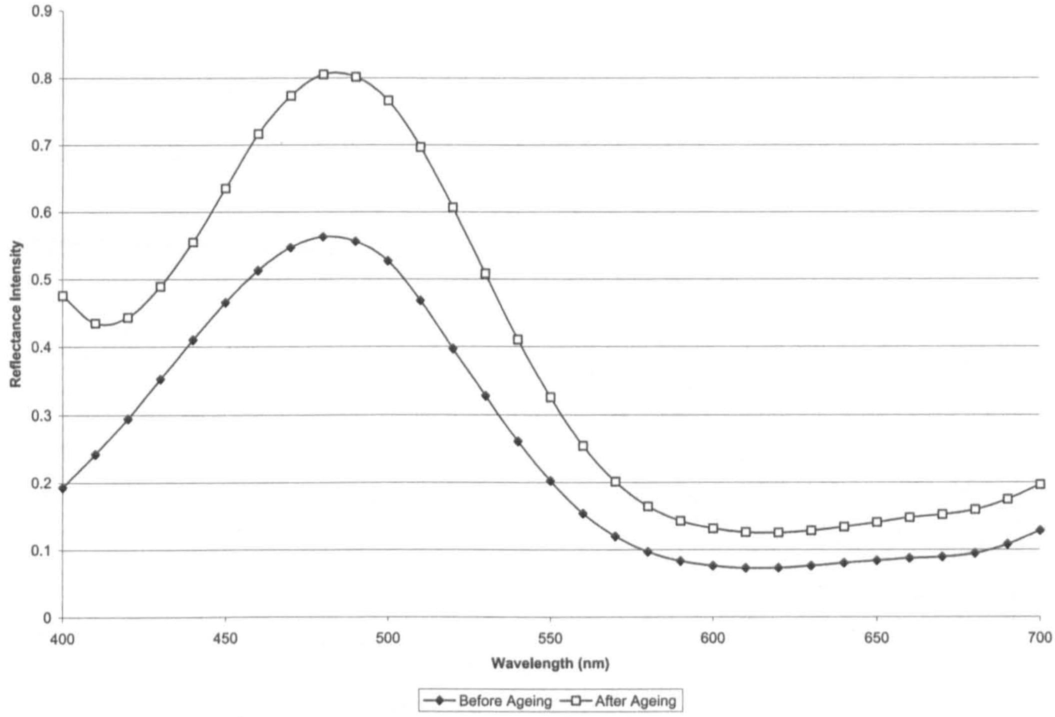
K.16 Plot showing the change in reflectance spectra of the magenta ink from the Lysonic ink set printed on Whatman watercolour paper (2.3) after exposure to daylight for 50,863 klux hours unfiltered.



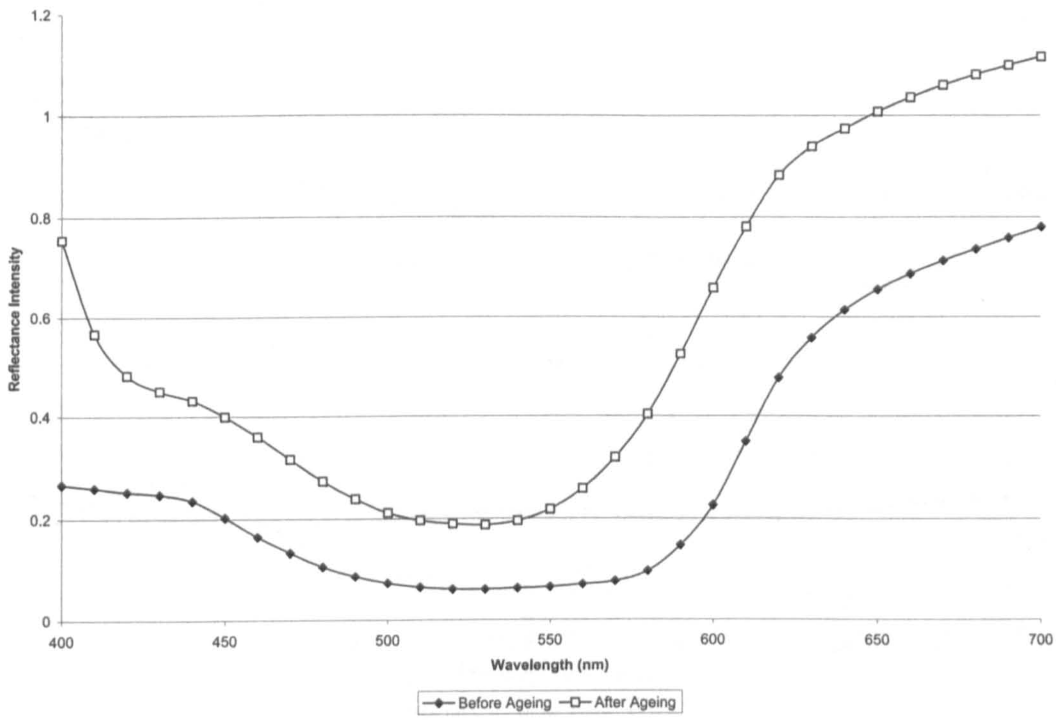
K.17 Plot showing the change in reflectance spectra of the yellow ink from the Lysonic ink set printed on Whatman watercolour paper (2.3) after exposure to daylight for 50,863 klux hours unfiltered.



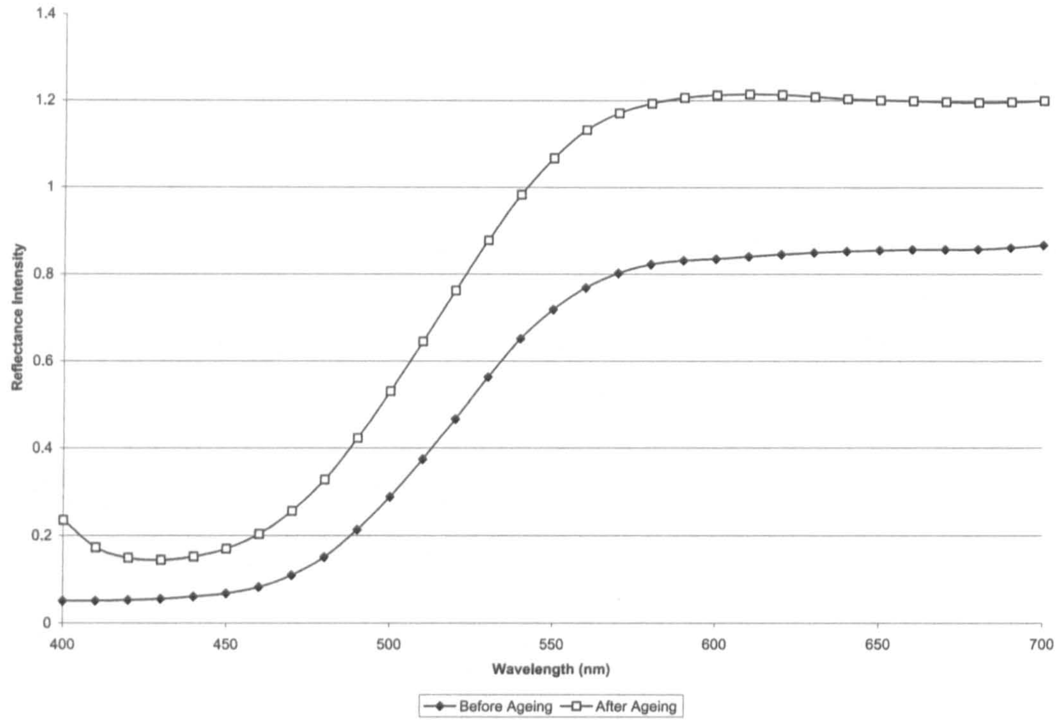
K.18 Plot showing the change in reflectance spectra of the black ink from the Lysonic ink set printed on Whatman watercolour paper (2.3) after exposure to daylight for 50,863 klux hours unfiltered.



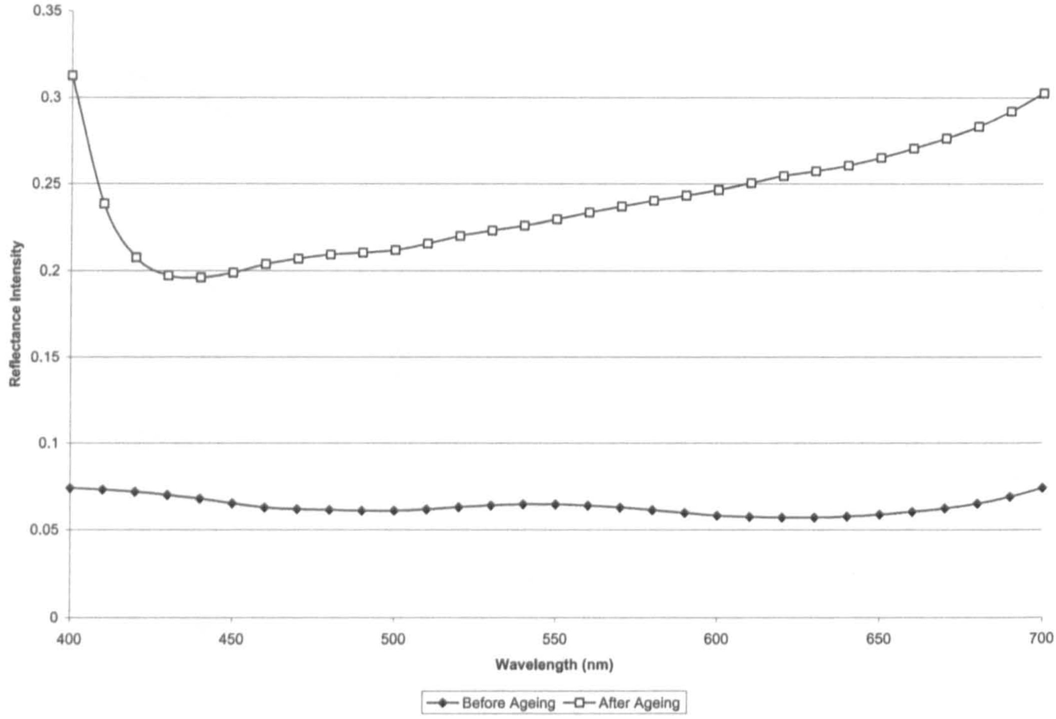
K.19 Plot showing the change in reflectance spectra of the cyan ink from the Fotonic ink set printed on Whatman watercolour paper (2.4) after exposure to daylight for 50,863 klux hours unfiltered.



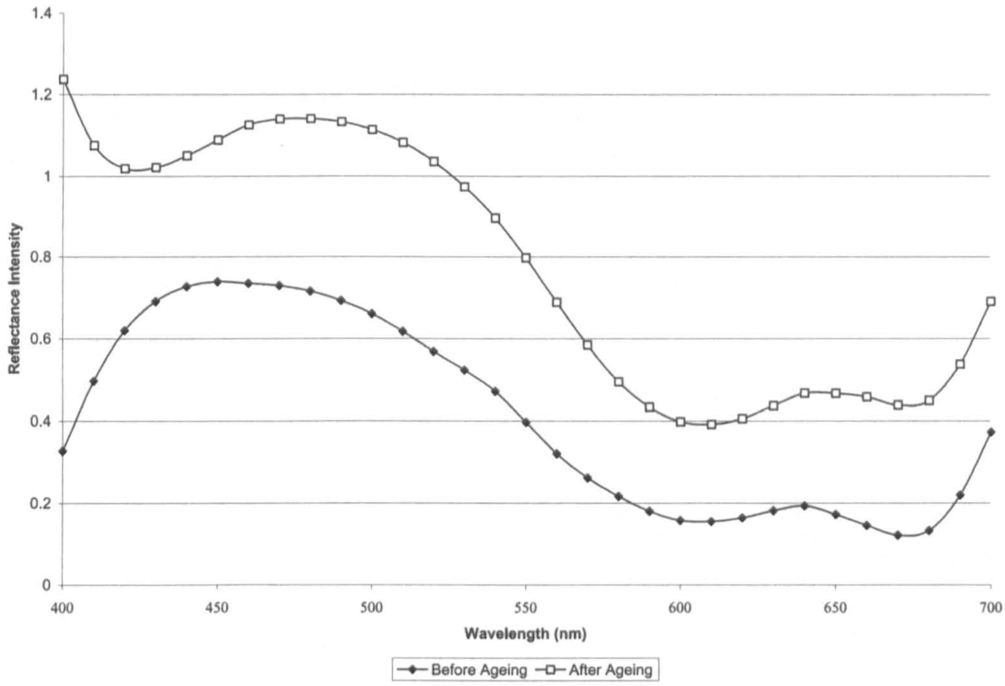
K.20 Plot showing the change in reflectance spectra of the magenta ink from the Fotonic ink set printed on Whatman watercolour paper (2.4) after exposure to daylight for 50,863 klux hours unfiltered.



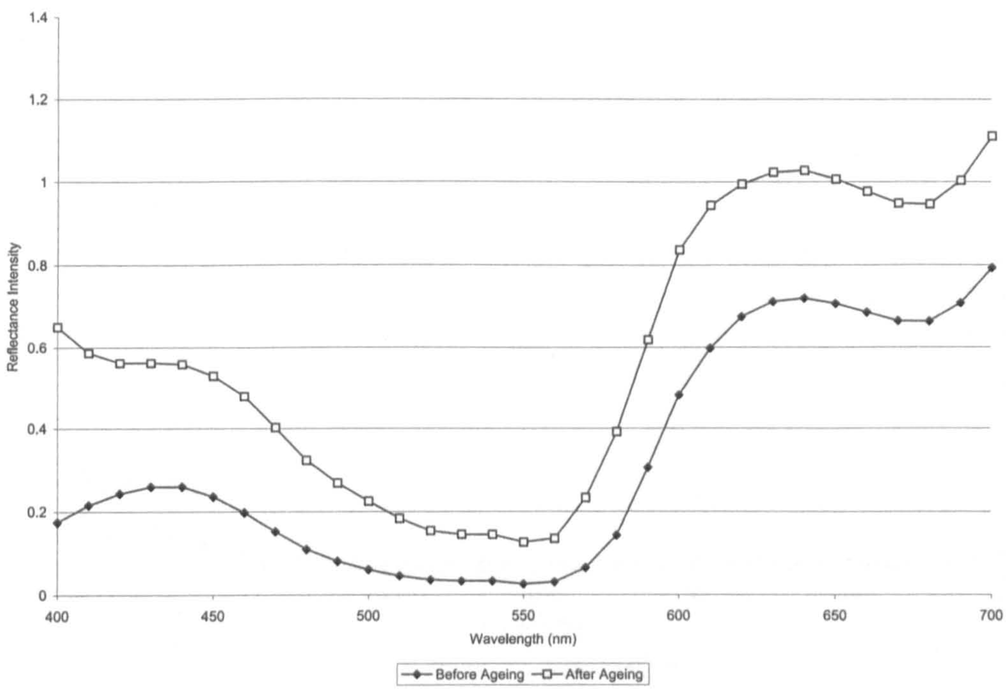
K.21 Plot showing the change in reflectance spectra of the yellow ink from the Fotonic ink set printed on Whatman watercolour paper (2.4) after exposure to daylight for 50,863 klux hours unfiltered.



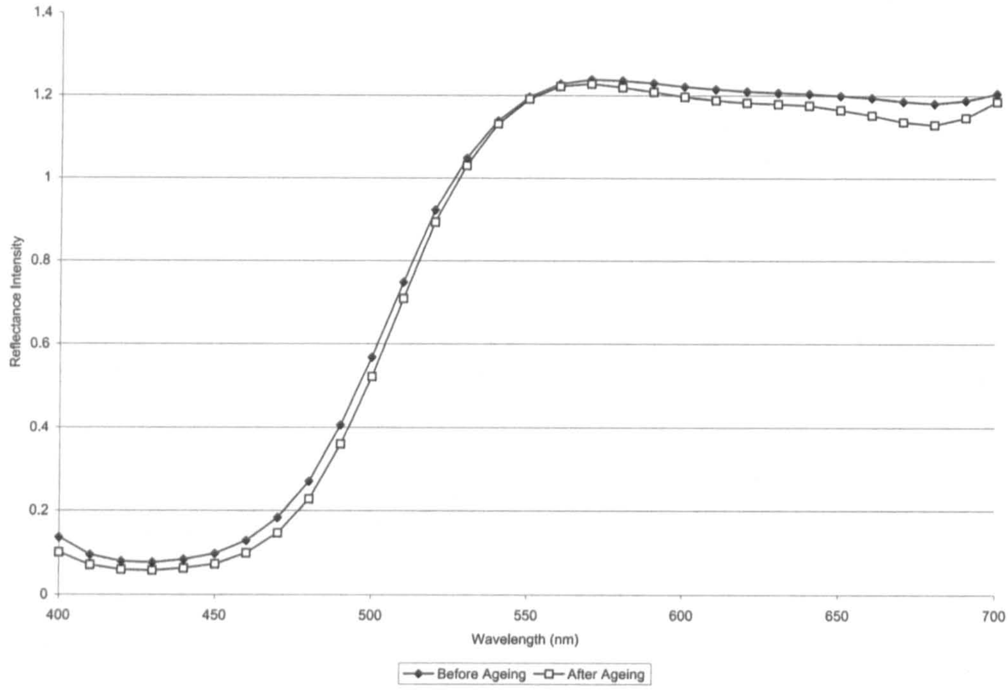
K.22 Plot showing the change in reflectance spectra of the black ink from the Fotonic ink set printed on Whatman watercolour paper (2.4) after exposure to daylight for 50,863 klux hours unfiltered.



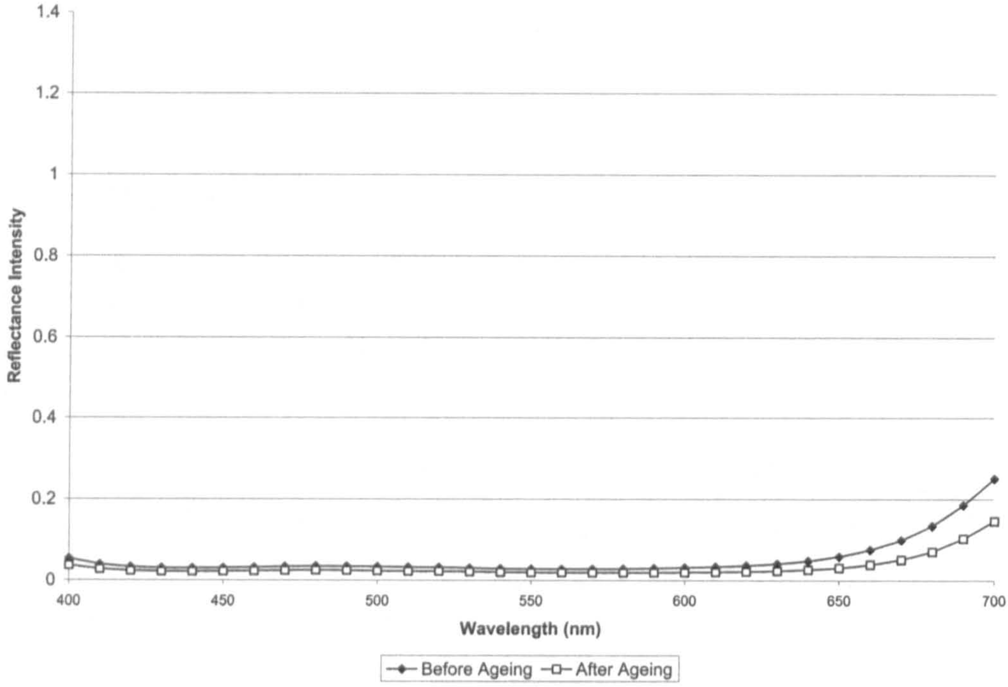
K.23 Plot showing the change in reflectance spectra of the cyan ink from the Epson Pro 9000 ink set printed on Epson Photo Glossy paper (3.1) after exposure to daylight for 50,863 klux hours unfiltered.



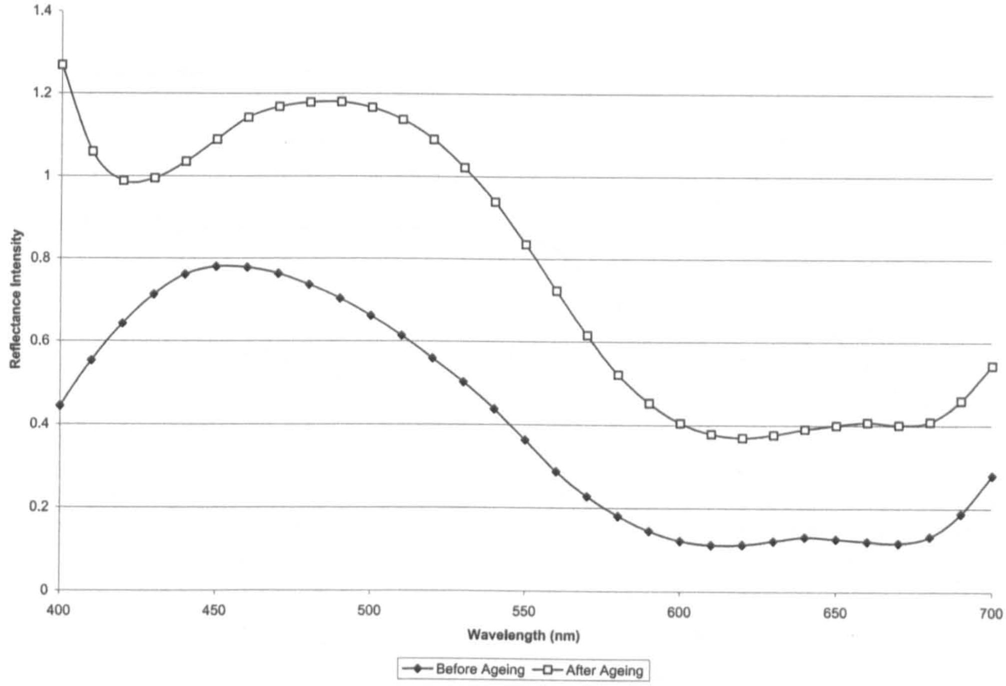
K.24 Plot showing the change in reflectance spectra of the magenta ink from the Epson Pro 9000 ink set printed on Epson Photo Glossy paper (3.1) after exposure to daylight for 50,863 klux hours unfiltered.



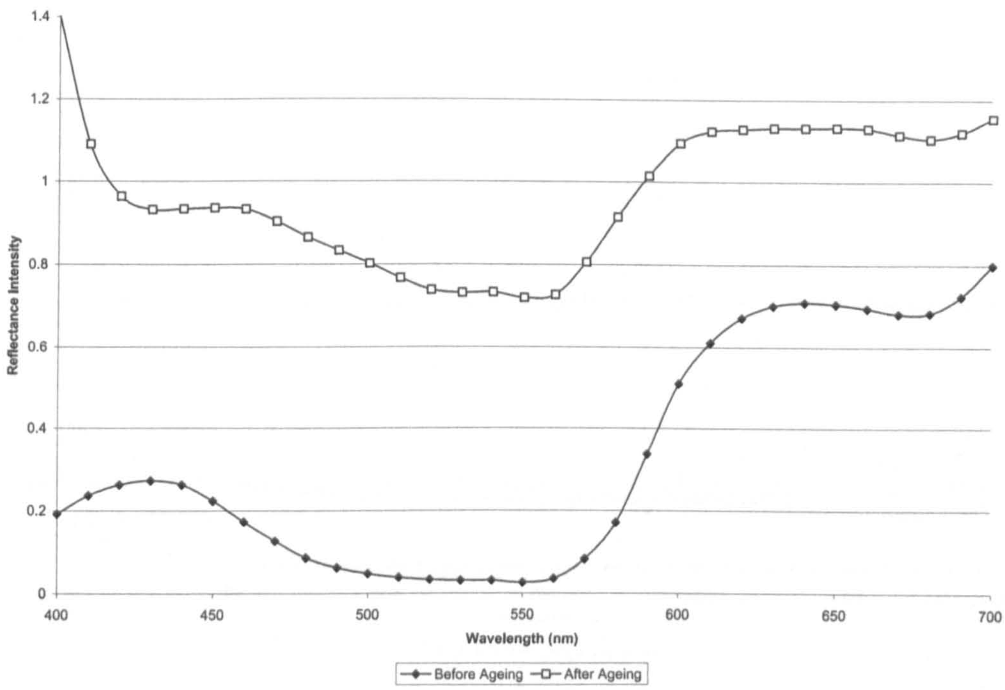
K.25 Plot showing the change in reflectance spectra of the yellow ink from the Epson Pro 9000 ink set printed on Epson Photo Glossy paper (3.1) after exposure to daylight for 50,863 klux hours unfiltered.



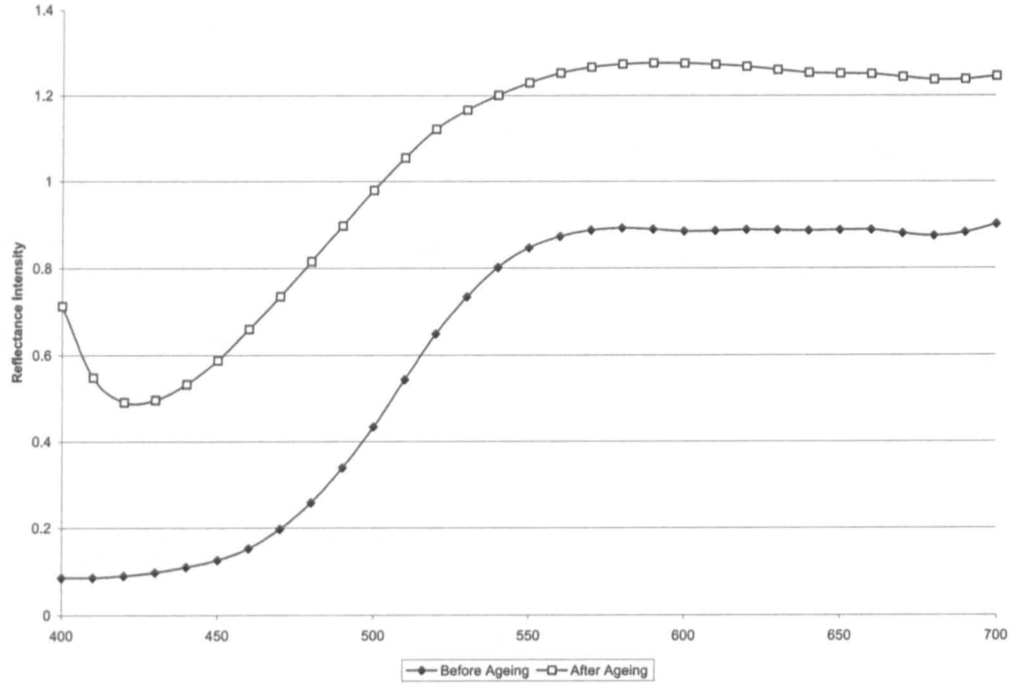
K.26 Plot showing the change in reflectance spectra of the black ink from the Epson Pro 9000 ink set printed on Epson Photo Glossy paper (3.1) after exposure to daylight for 50,863 klux hours unfiltered.



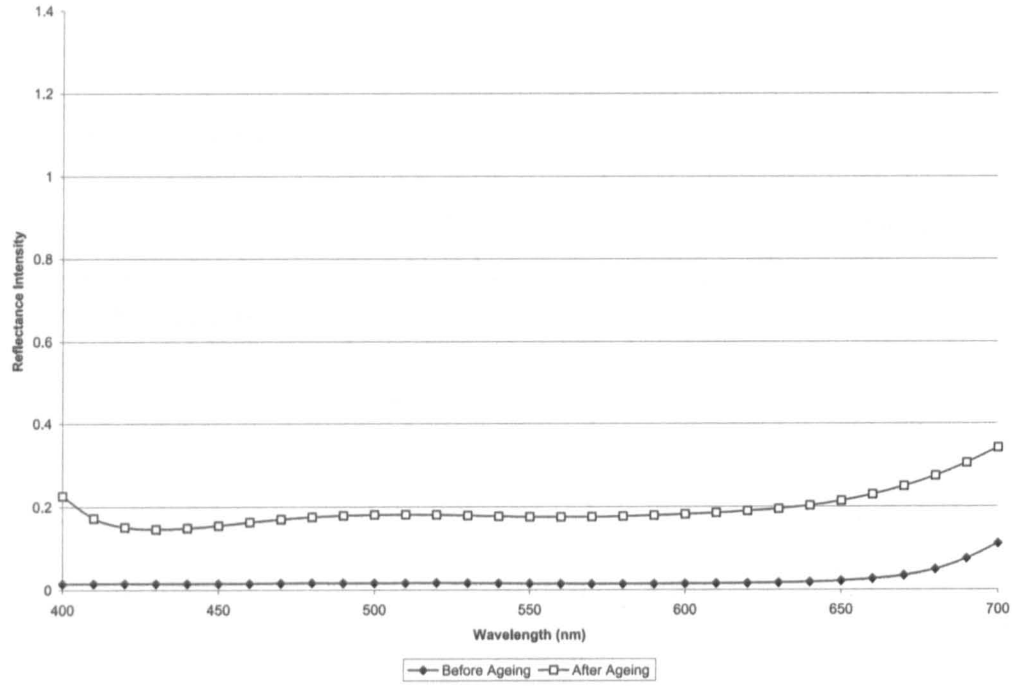
K.27 Plot showing the change in reflectance spectra of the cyan ink from the Epson Pro 9000 ink set printed on ISVE paper (3.2) after exposure to daylight for 50,863 klux hours unfiltered.



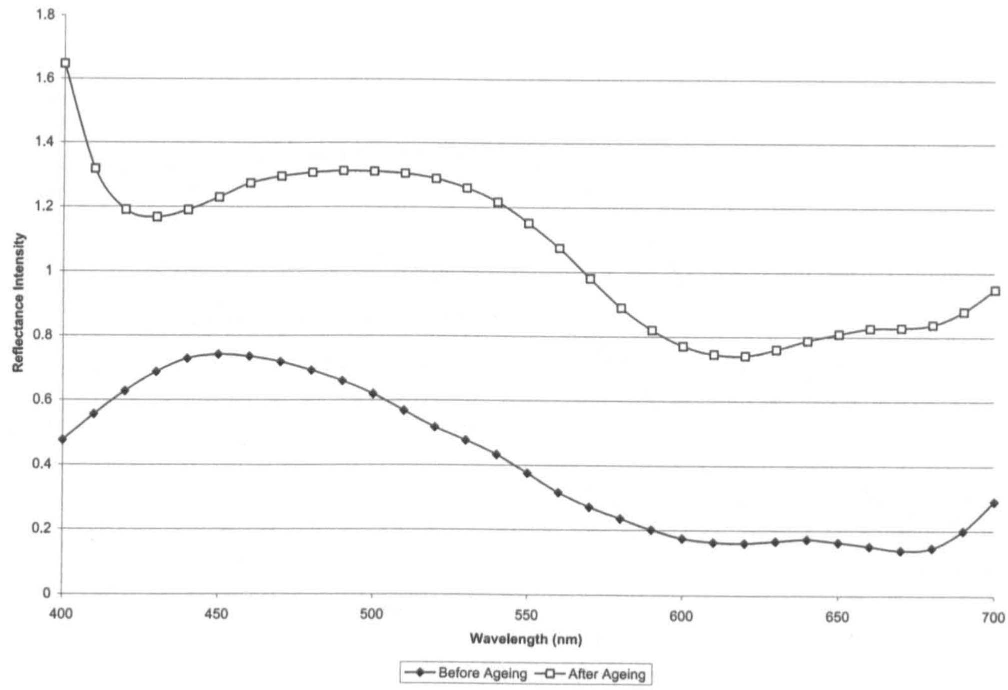
K.28 Plot showing the change in reflectance spectra of the magenta ink from the Epson Pro 9000 ink set printed on ISVE paper (3.2) after exposure to daylight for 50,863 klux hours unfiltered.



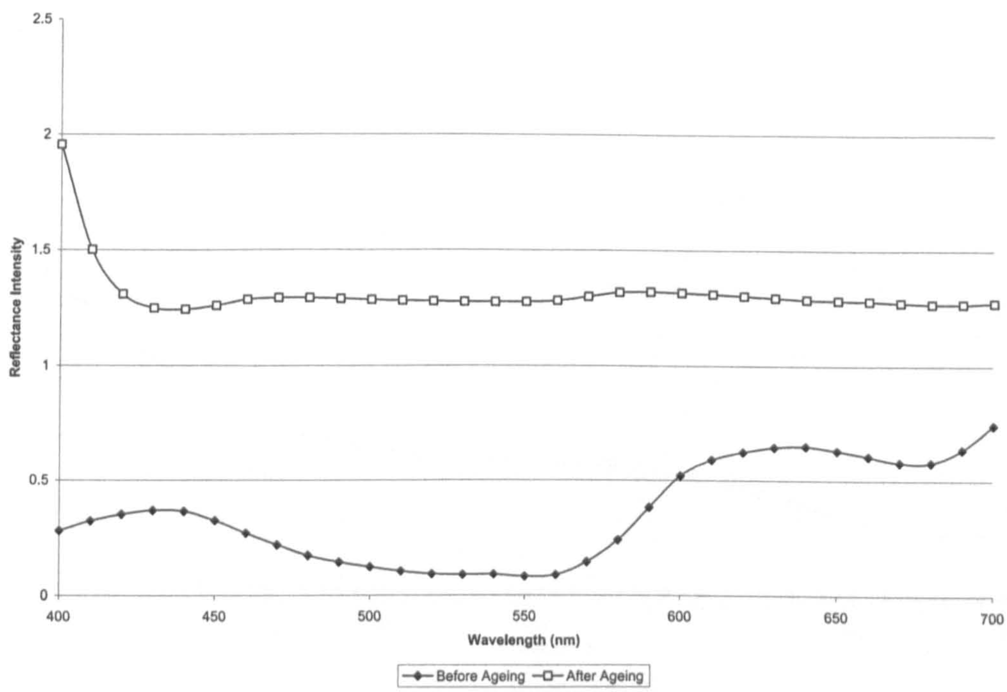
K.29 Plot showing the change in reflectance spectra of the yellow ink from the Epson Pro 9000 ink set printed on ISVE paper (3.2) after exposure to daylight for 50,863 klux hours unfiltered.



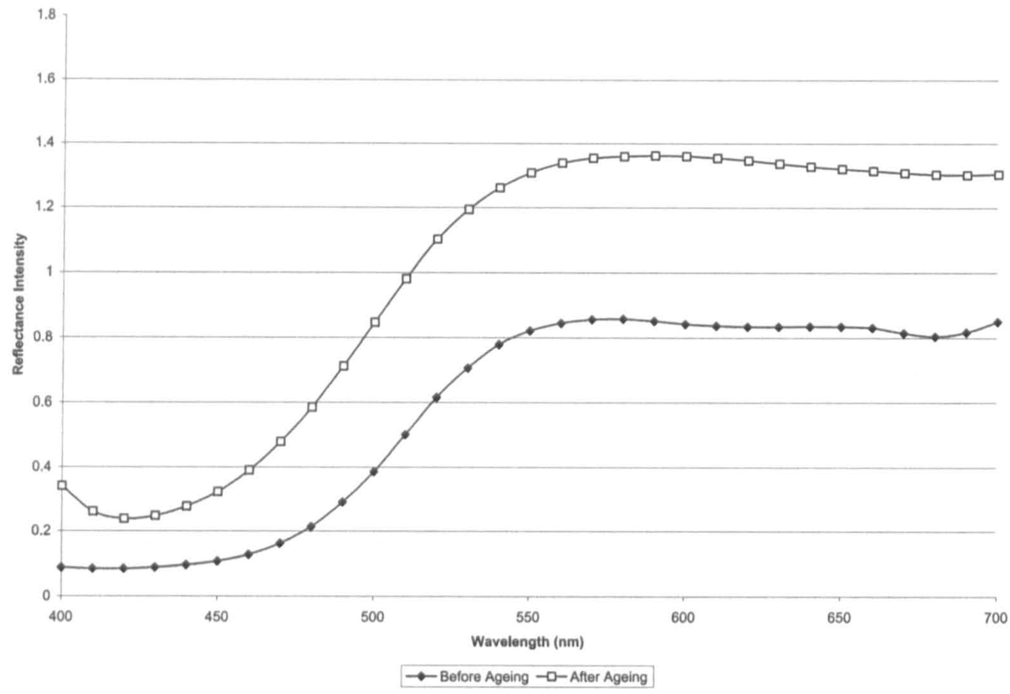
K.30 Plot showing the change in reflectance spectra of the black ink from the Epson Pro 9000 ink set printed on ISVE paper (3.2) after exposure to daylight for 50,863 klux hours unfiltered.



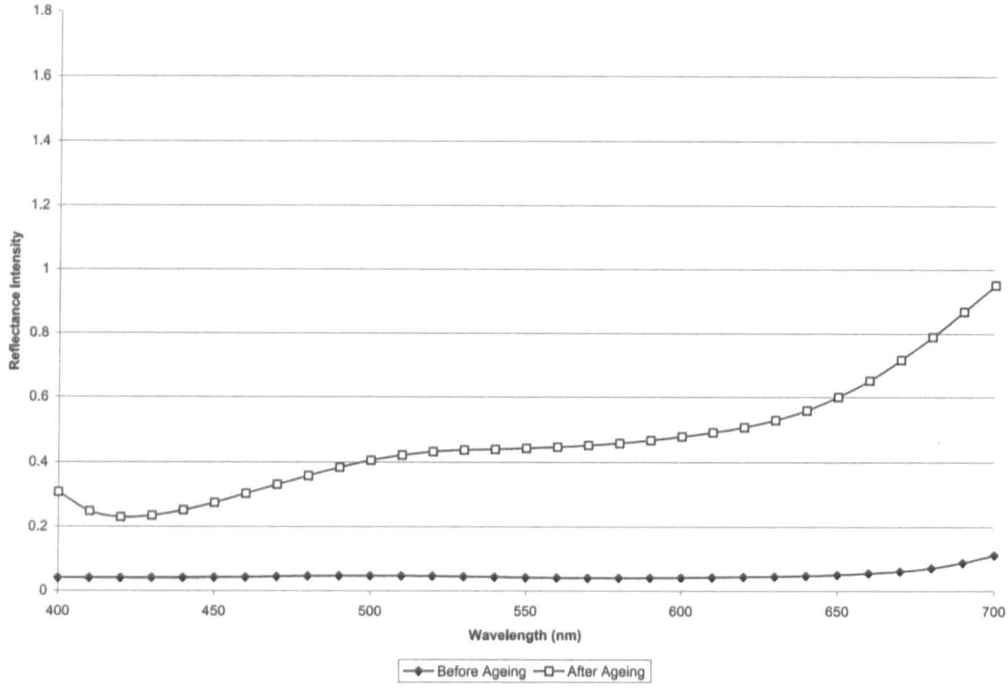
K.31 Plot showing the change in reflectance spectra of the cyan ink from the Epson Pro 9000 ink set printed on Whatman watercolour paper (3.4) after exposure to daylight for 50,863 klux hours unfiltered.



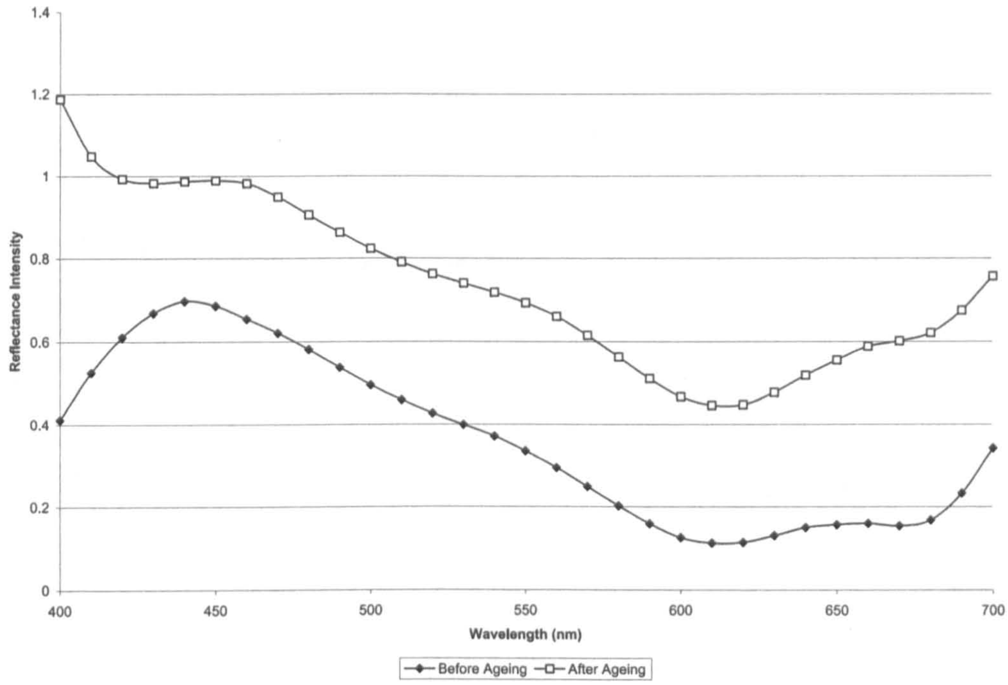
K.32 Plot showing the change in reflectance spectra of the magenta ink from the Epson Pro 9000 ink set printed on Whatman watercolour paper (3.4) after exposure to daylight for 50,863 klux hours unfiltered.



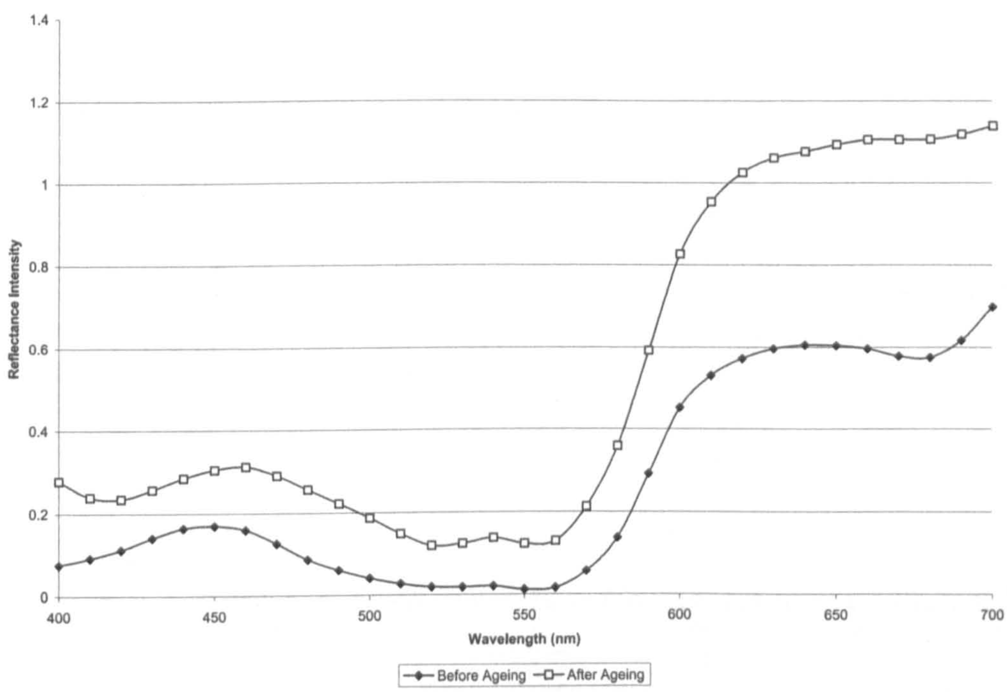
K.33 Plot showing the change in reflectance spectra of the yellow ink from the Epson Pro 9000 ink set printed on Whatman watercolour paper (3.4) after exposure to daylight for 50,863 klux hours unfiltered.



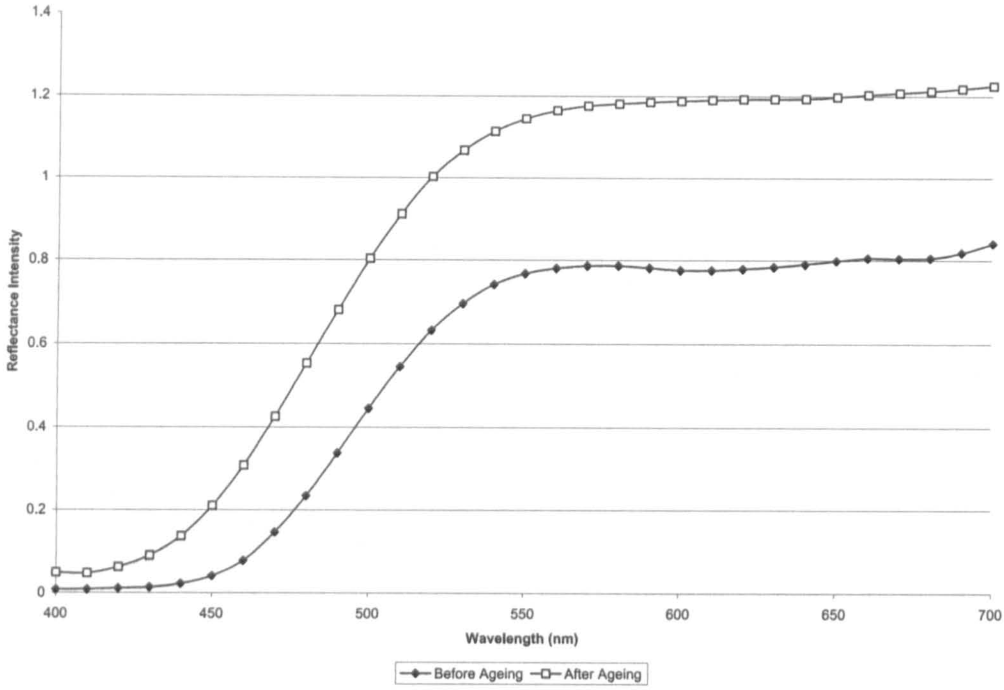
K.34 Plot showing the change in reflectance spectra of the black ink from the Epson Pro 9000 ink set printed on Whatman watercolour paper (3.4) after exposure to daylight for 50,863 klux hours unfiltered.



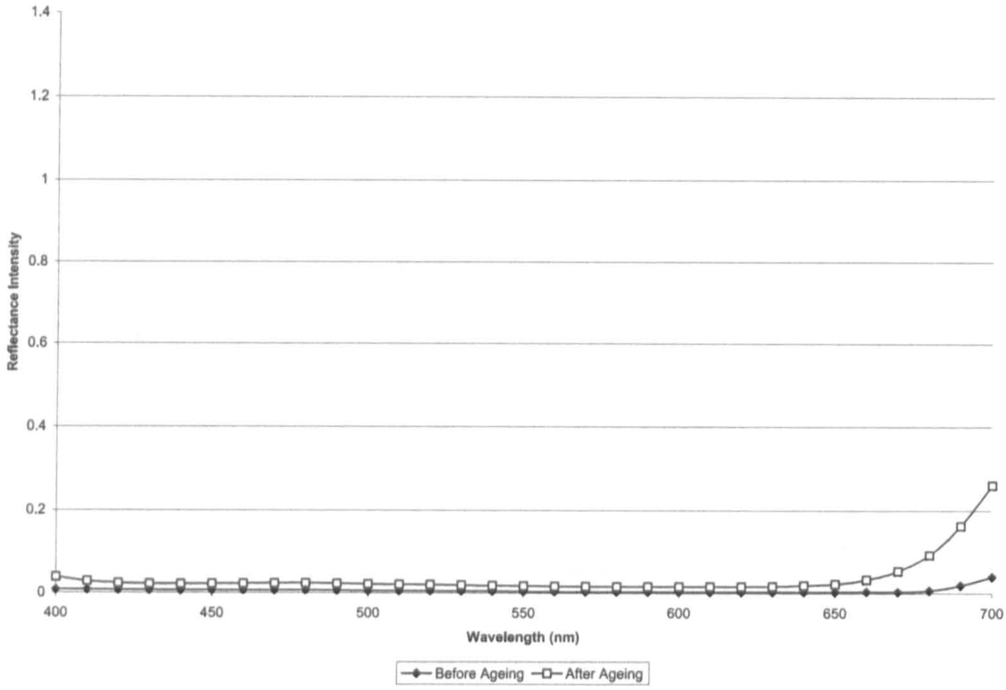
K.35 Plot showing the change in reflectance spectra of the cyan ink from the Epson Photo Stylus ink set printed on Epson Photo Glossy paper (3.6) after exposure to daylight for 50,863 klux hours unfiltered.



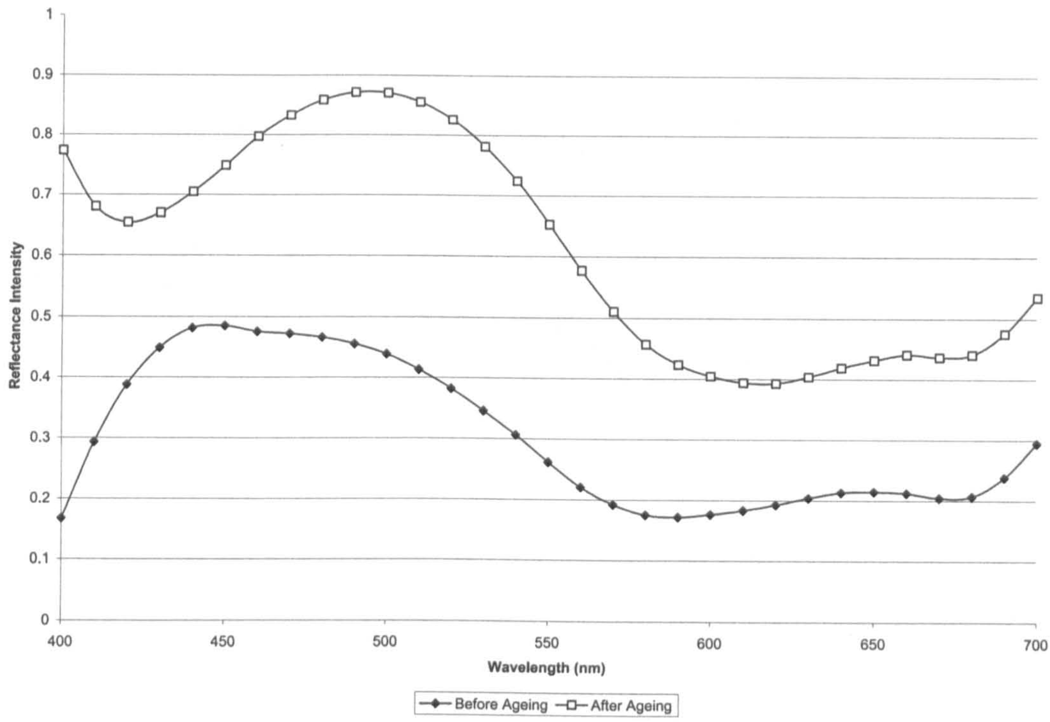
K.36 Plot showing the change in reflectance spectra of the magenta ink from the Epson Photo Stylus ink set printed on Epson Photo Glossy paper (3.6) after exposure to daylight for 50,863 klux hours unfiltered.



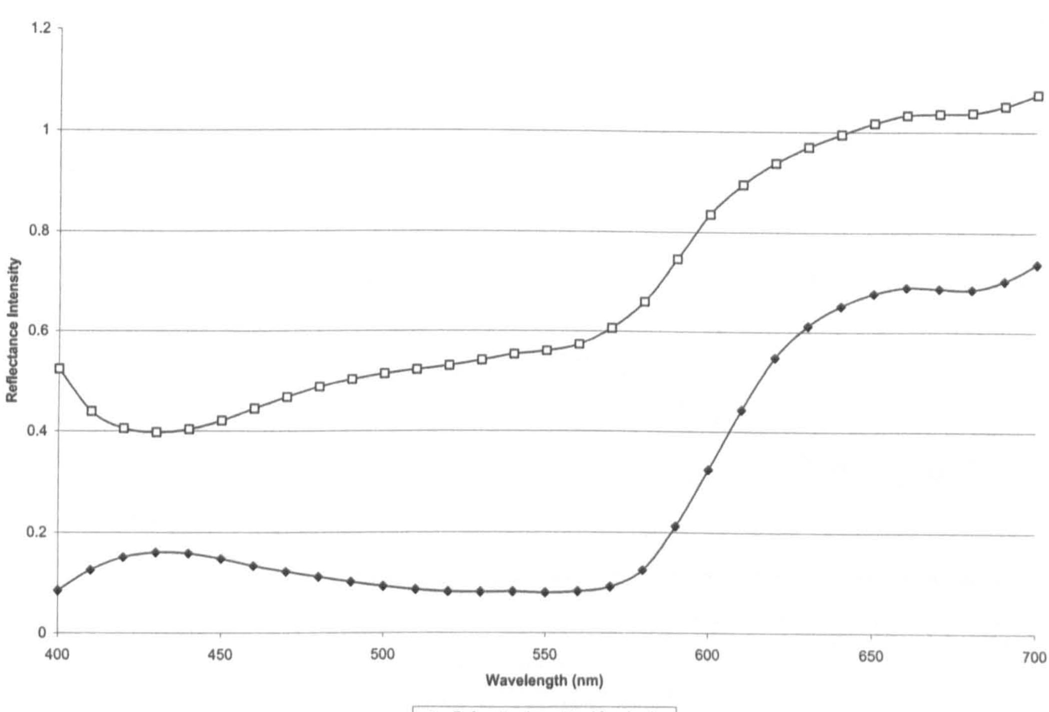
K.37 Plot showing the change in reflectance spectra of the yellow ink from the Epson Photo Stylus ink set printed on Epson Photo Glossy paper (3.6) after exposure to daylight for 50,863 klux hours unfiltered.



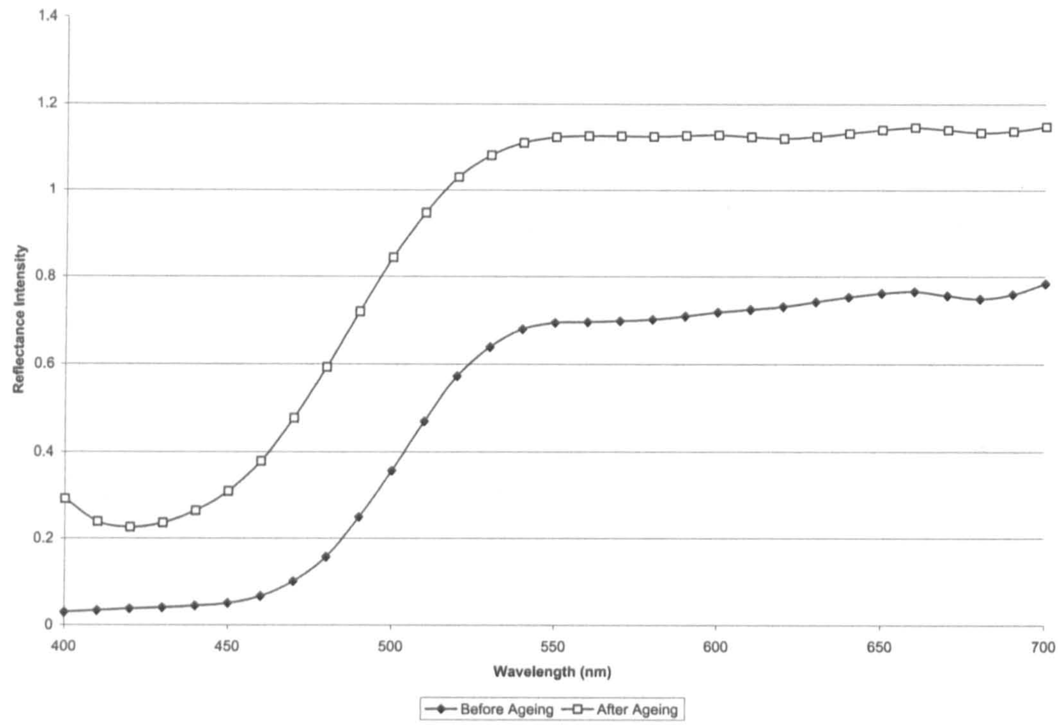
K.38 Plot showing the change in reflectance spectra of the black ink from the Epson Photo Stylus ink set printed on Epson Photo Glossy paper (3.6) after exposure to daylight for 50,863 klux hours unfiltered.



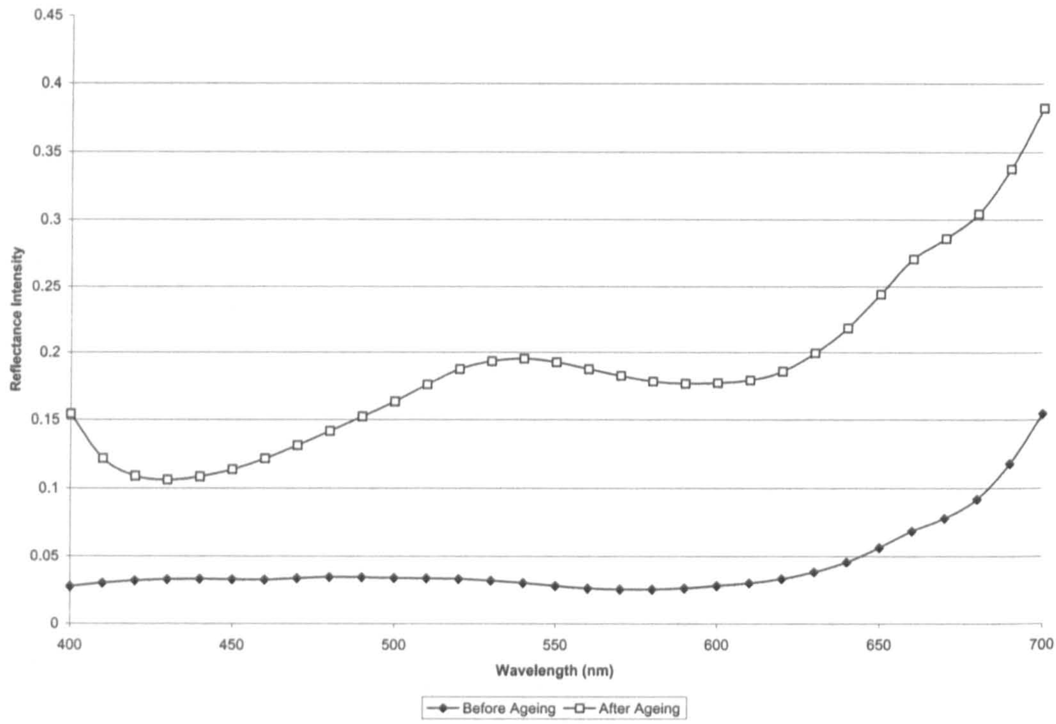
K.39 Plot showing the change in reflectance spectra of the cyan ink from the HP 3500 ink set printed on HP Heavy Weight paper (4.1) after exposure to daylight for 50,863 klux hours unfiltered.



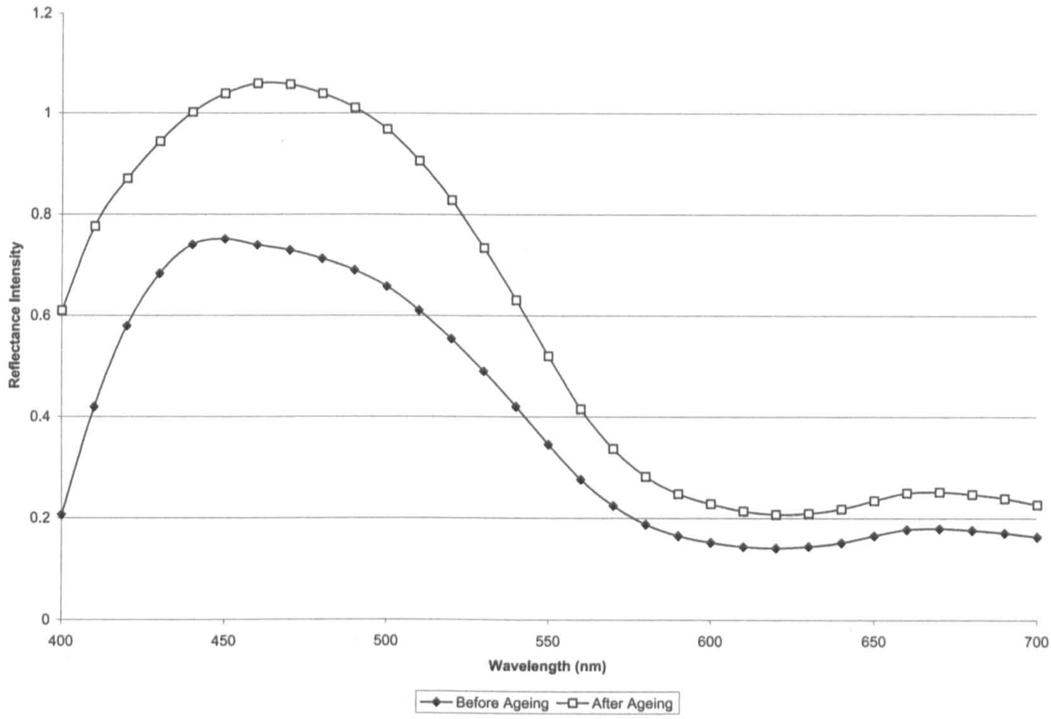
K.40 Plot showing the change in reflectance spectra of the magenta ink from the HP 3500 ink set printed on HP Heavy Weight paper (4.1) after exposure to daylight for 50,863 klux hours unfiltered.



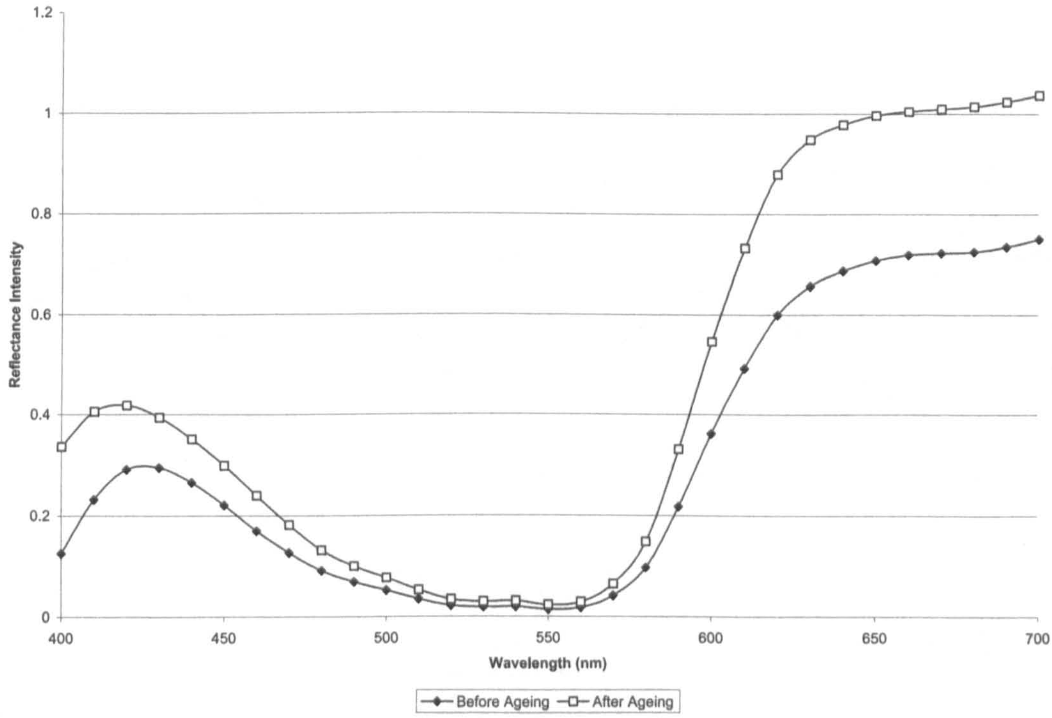
K.41 Plot showing the change in reflectance spectra of the yellow ink from the HP 3500 ink set printed on HP Heavy Weight paper (4.1) after exposure to daylight for 50,863 klux hours unfiltered.



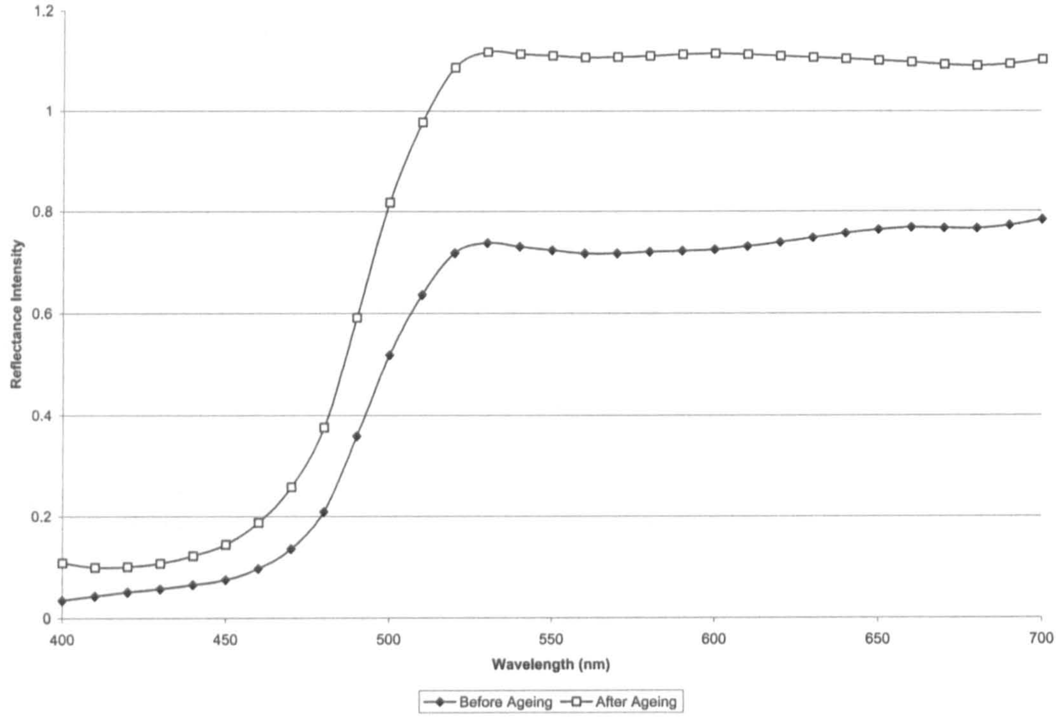
K.42 Plot showing the change in reflectance spectra of the black ink from the HP 3500 ink set printed on HP Heavy Weight paper (4.1) after exposure to daylight for 50,863 klux hours unfiltered.



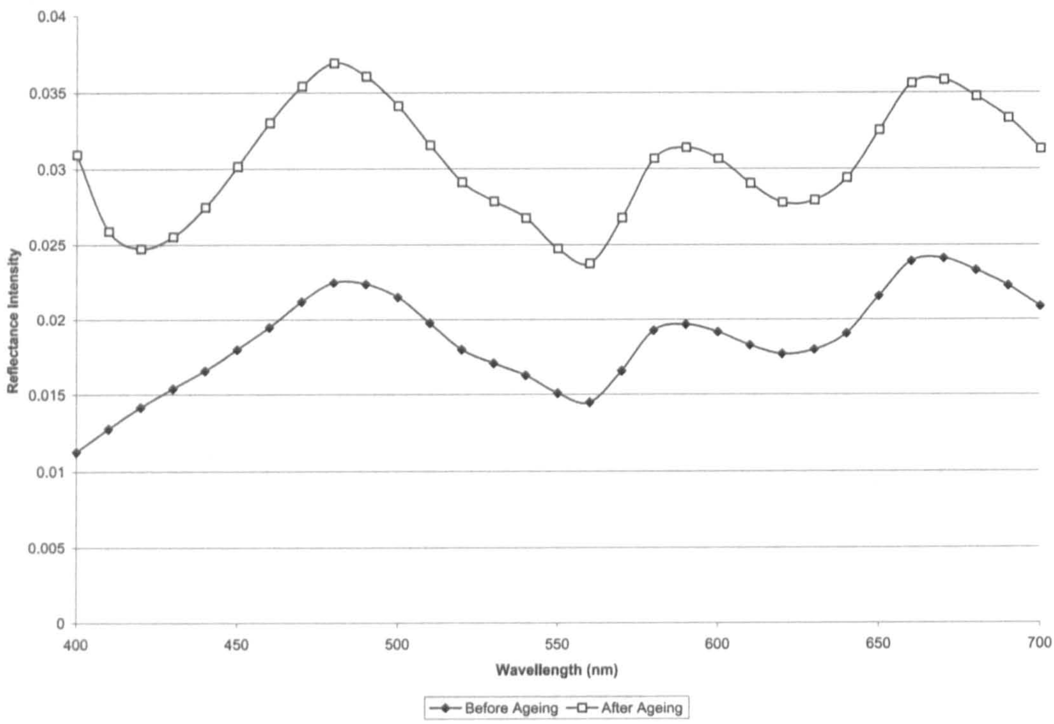
K.43 Plot showing the change in reflectance spectra of the cyan toner from the Canon 1150 laser ink set printed on Canon Ultra White paper (5.1) after exposure to daylight for 50,863 klux hours unfiltered.



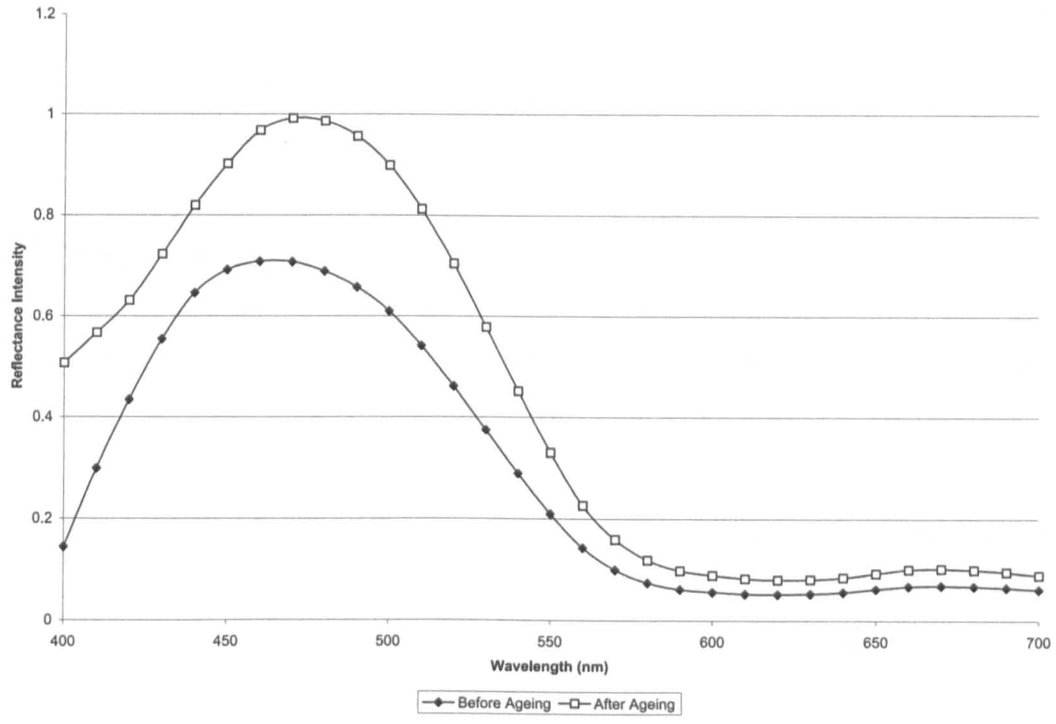
K.44 Plot showing the change in reflectance spectra of the magenta toner from the Canon 1150 laser ink set printed on Canon Ultra White paper (5.1) after exposure to daylight for 50,863 klux hours unfiltered.



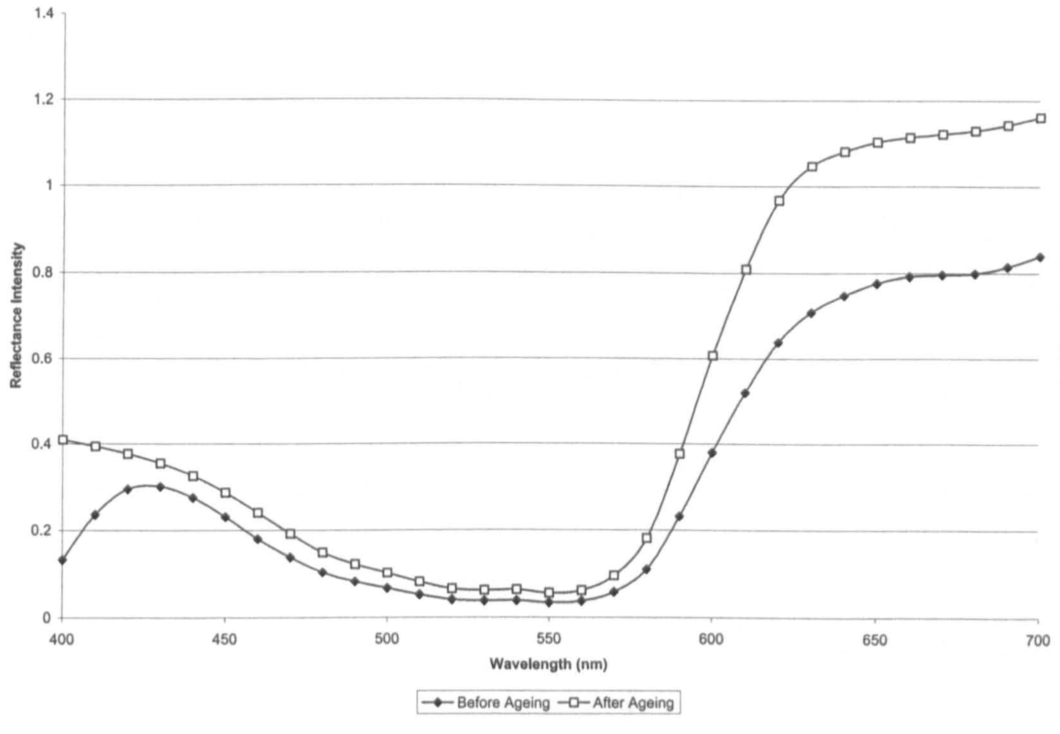
K.45 Plot showing the change in reflectance spectra of the yellow toner from the Canon 1150 laser ink set printed on Canon Ultra White paper (5.1) after exposure to daylight for 50,863 klux hours unfiltered.



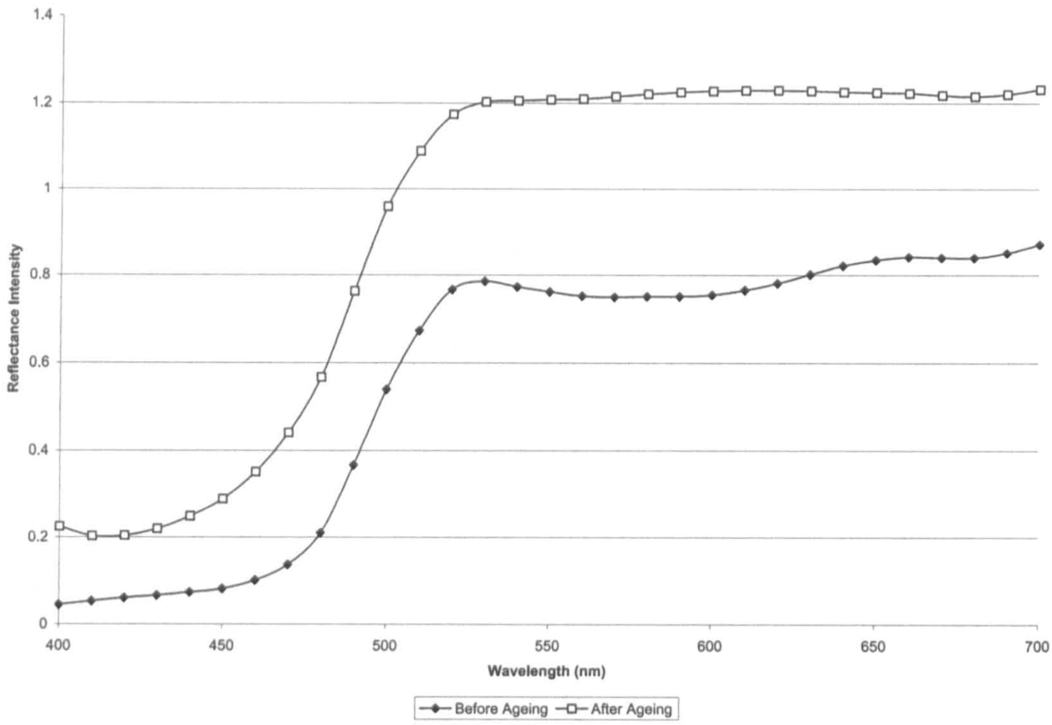
K.46 Plot showing the change in reflectance spectra of the black toner from the Canon 1150 laser ink set printed on Canon Ultra White paper (5.1) after exposure to daylight for 50,863 klux hours unfiltered.



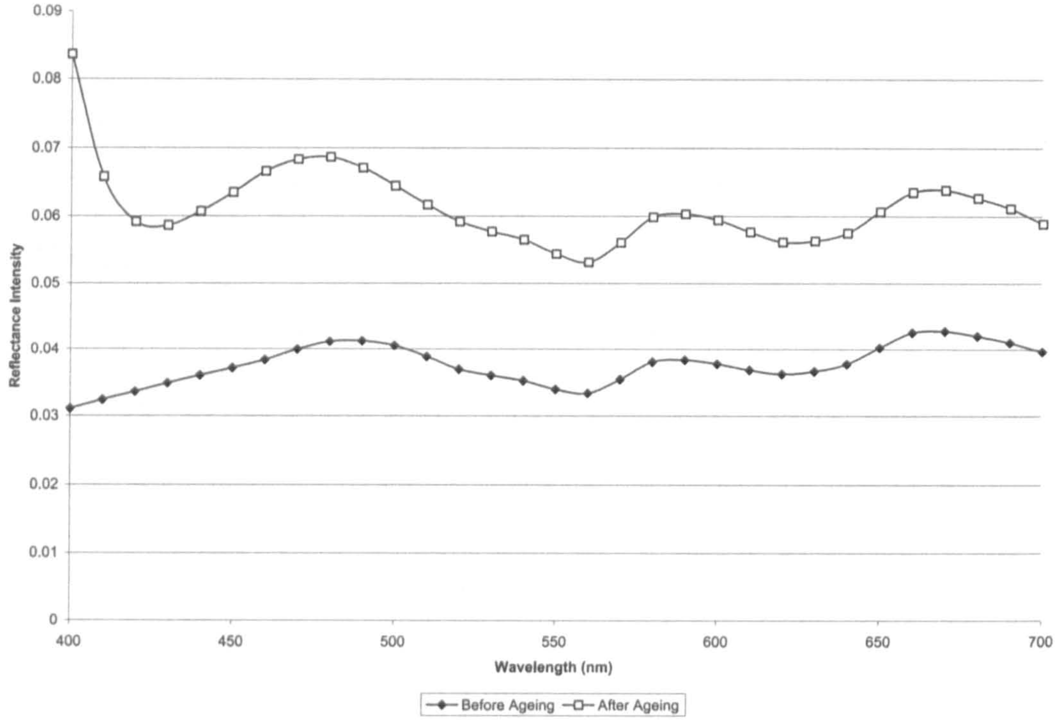
K.47 Plot showing the change in reflectance spectra of the cyan toner from the Canon 1150 laser ink set printed on Canon Card (5.2) after exposure to daylight for 50,863 klux hours unfiltered.



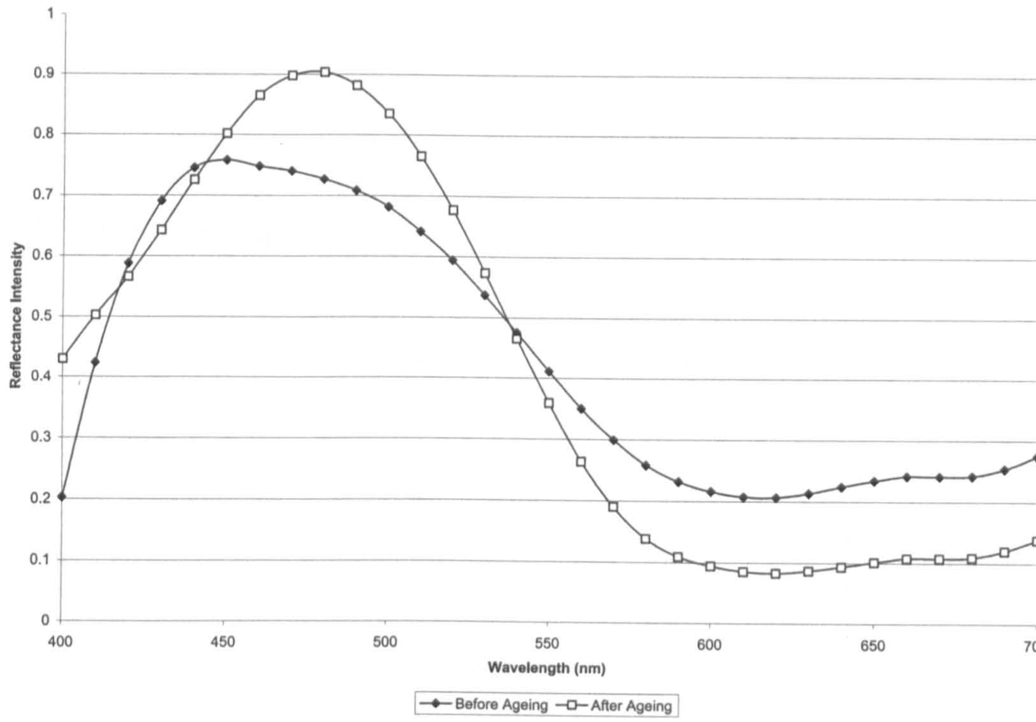
K.48 Plot showing the change in reflectance spectra of the magenta toner from the Canon 1150 laser ink set printed on Canon Card (5.2) after exposure to daylight for 50,863 klux hours unfiltered.



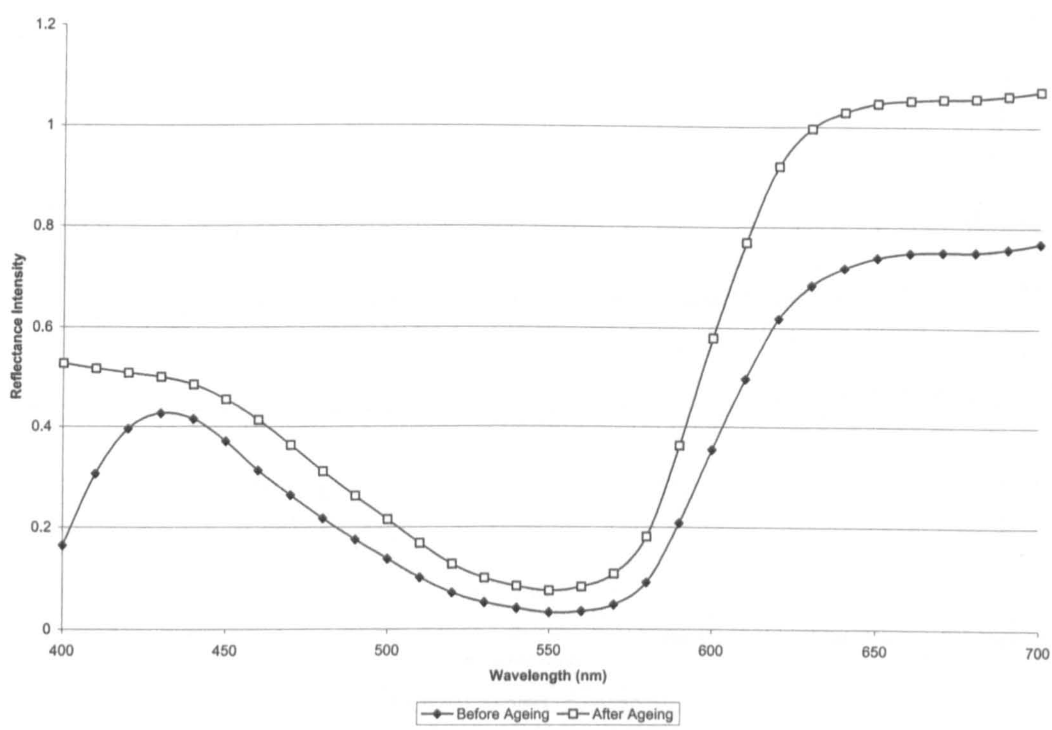
K.49 Plot showing the change in reflectance spectra of the yellow toner from the Canon 1150 laser ink set printed on Canon Card (5.2) after exposure to daylight for 50,863 klux hours unfiltered.



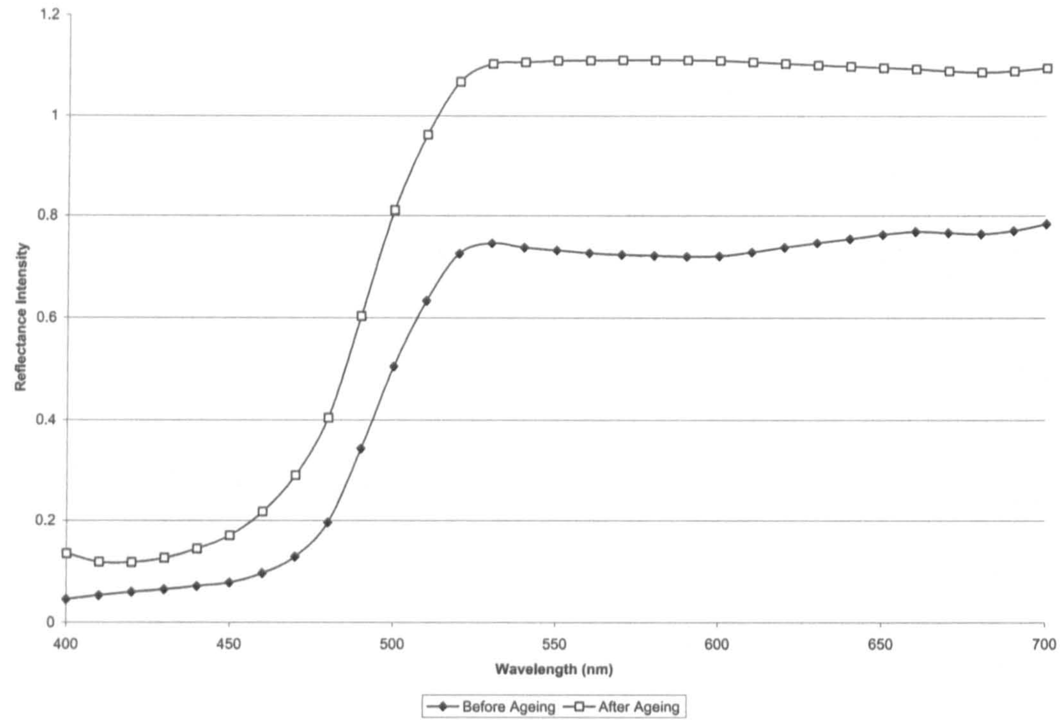
K.50 Plot showing the change in reflectance spectra of the black toner from the Canon 1150 laser ink set printed on Canon Card (5.2) after exposure to daylight for 50,863 klux hours unfiltered.



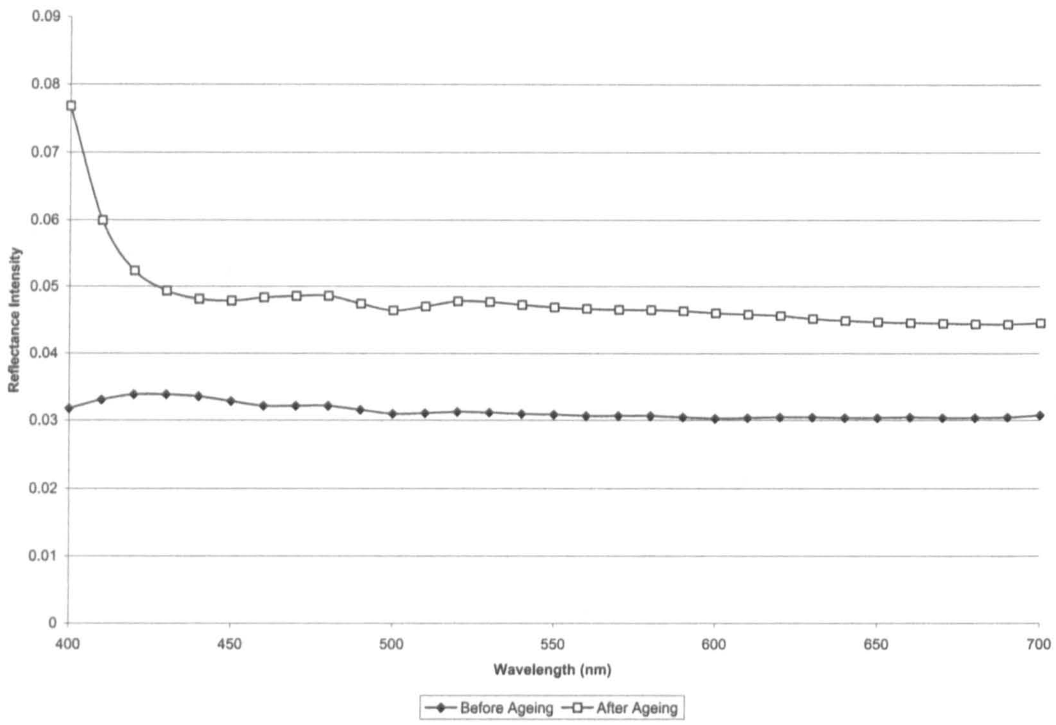
K.51 Plot showing the change in reflectance spectra of the cyan toner from the Canon CLC 900 ink set printed on Canon Ultra White paper (5.3) after exposure to daylight for 50,863 klux hours unfiltered.



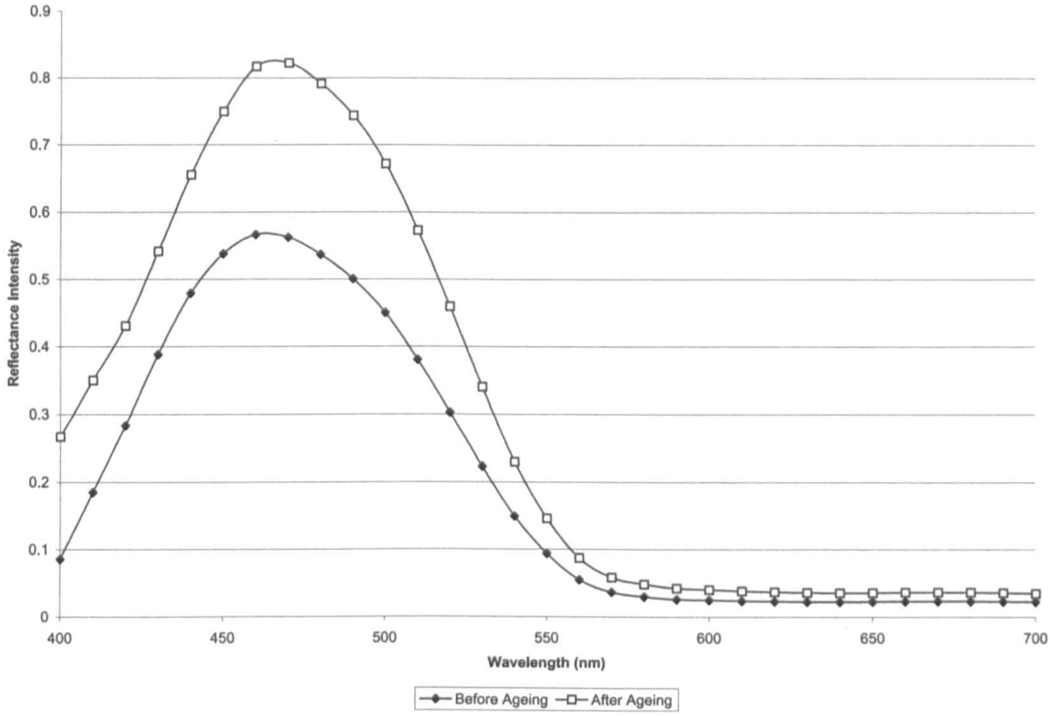
K.52 Plot showing the change in reflectance spectra of the magenta toner from the Canon CLC 900 ink set printed on Canon Ultra White paper (5.3) after exposure to daylight for 50,863 klux hours unfiltered.



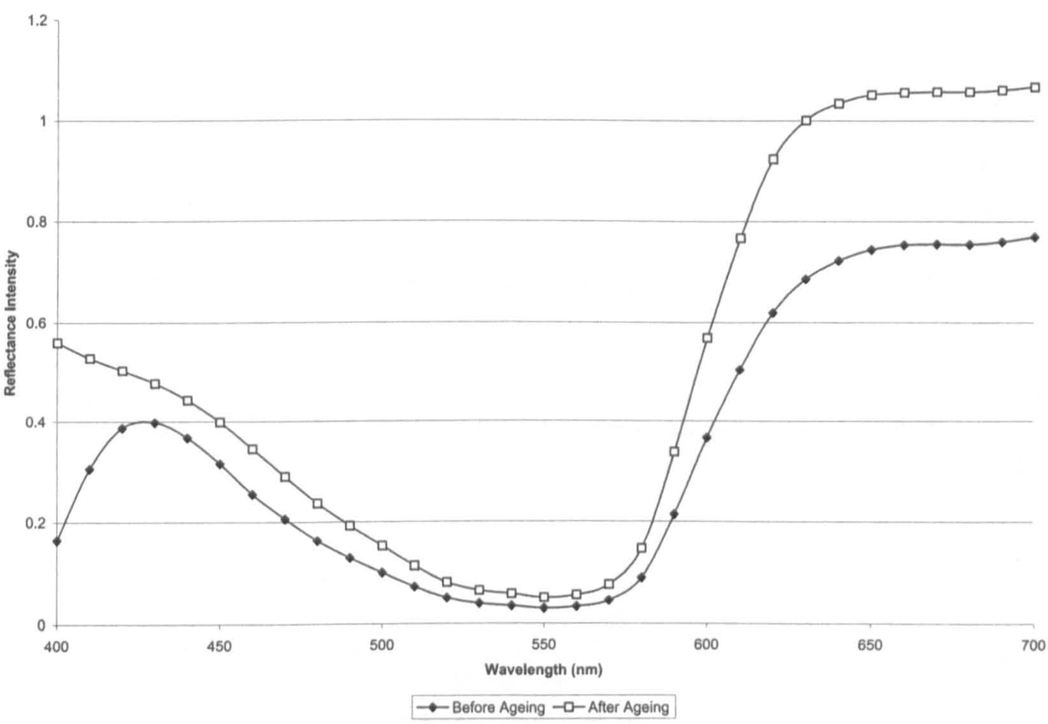
K.53 Plot showing the change in reflectance spectra of the yellow toner from the Canon CLC 900 ink set printed on Canon Ultra White paper (5.3) after exposure to daylight for 50,863 klux hours unfiltered.



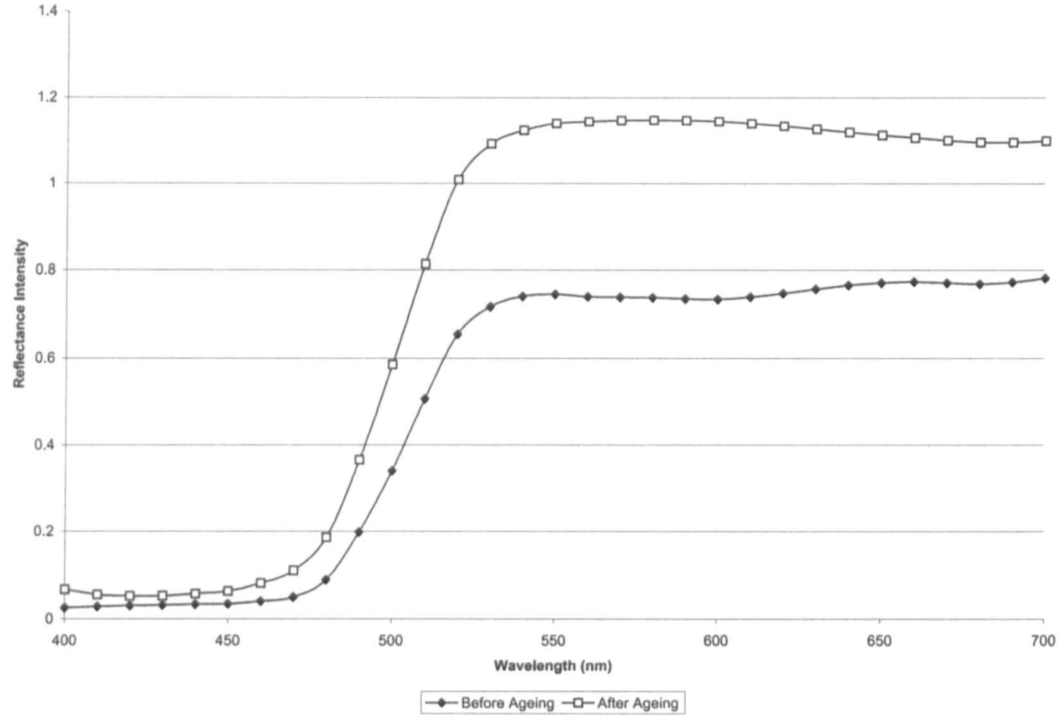
K.54 Plot showing the change in reflectance spectra of the black toner from the Canon CLC 900 ink set printed on Canon Ultra White paper (5.3) after exposure to daylight for 50,863 klux hours unfiltered.



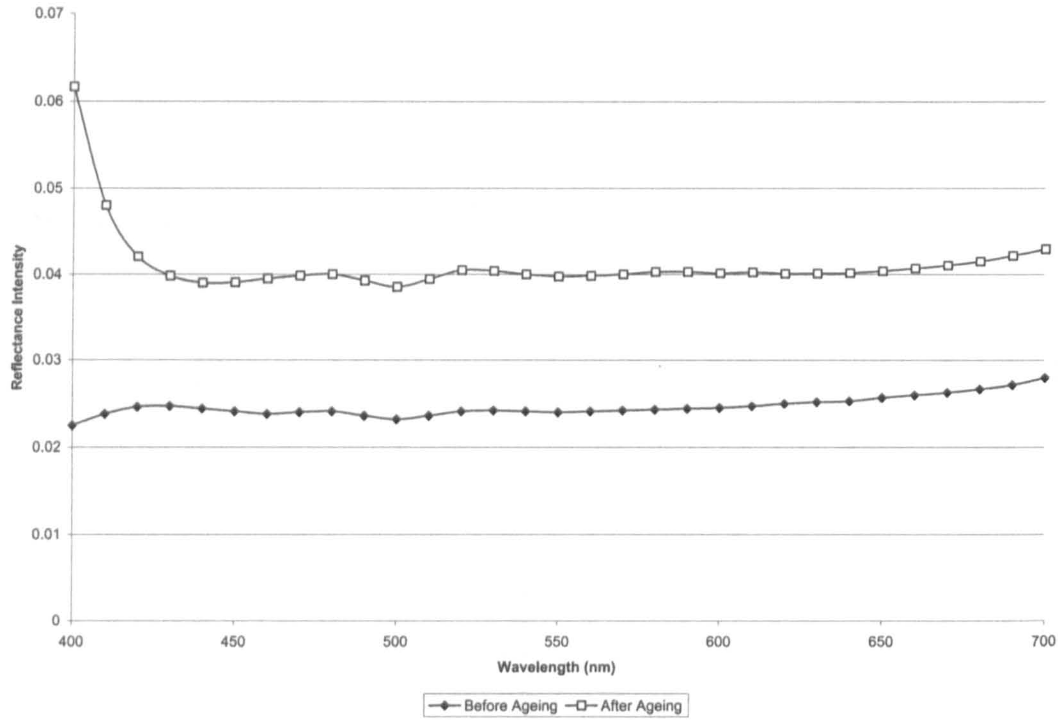
K.55 Plot showing the change in reflectance spectra of the cyan toner from the Canon CLBP 460PS ink set printed on Canon Ultra White paper (5.4) after exposure to daylight for 50,863 klux hours unfiltered.



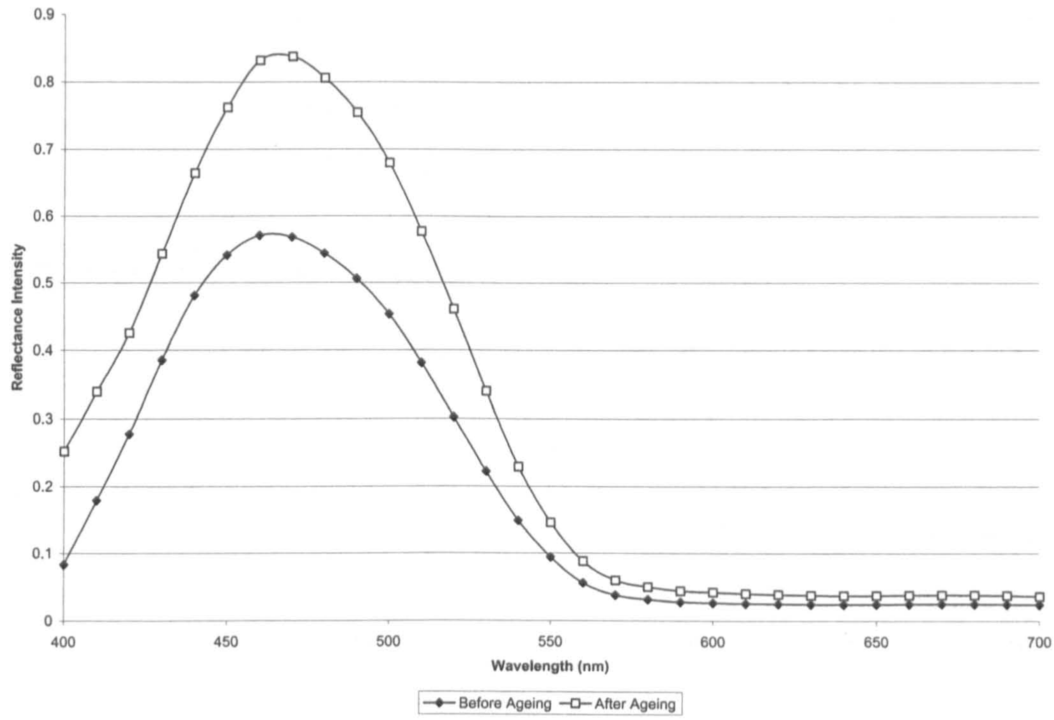
K.56 Plot showing the change in reflectance spectra of the magenta toner from the Canon CLBP 460PS ink set printed on Canon Ultra White paper (5.4) after exposure to daylight for 50,863 klux hours unfiltered.



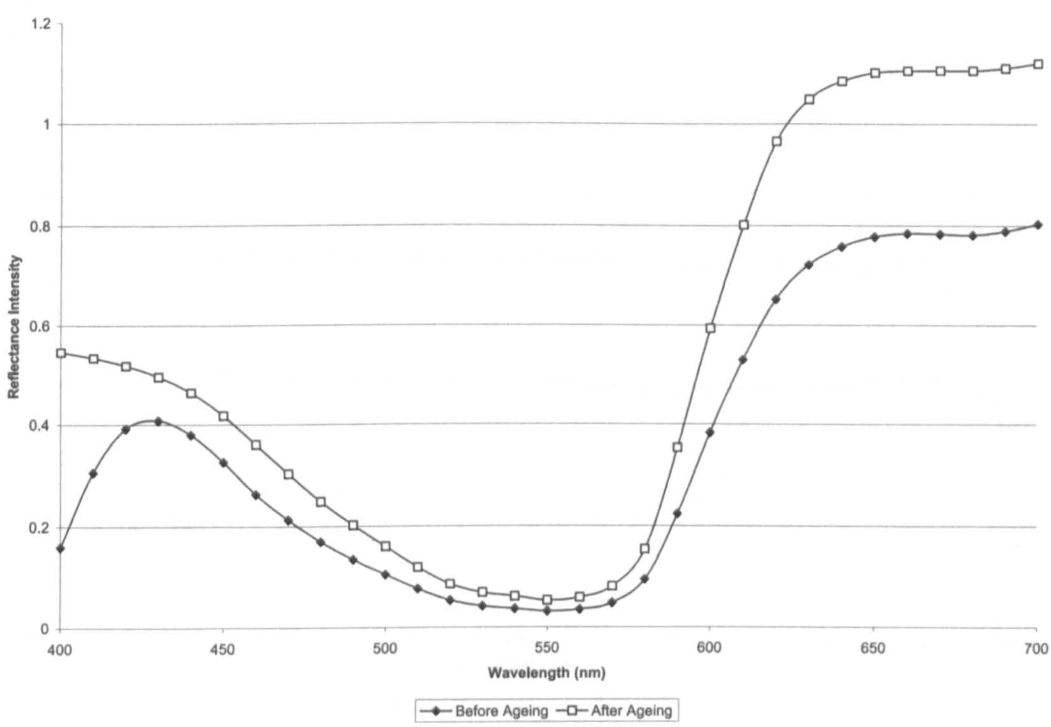
K.57 Plot showing the change in reflectance spectra of the yellow toner from the Canon CLBP 460PS ink set printed on Canon Ultra White paper (5.4) after exposure to daylight for 50,863 klux hours unfiltered.



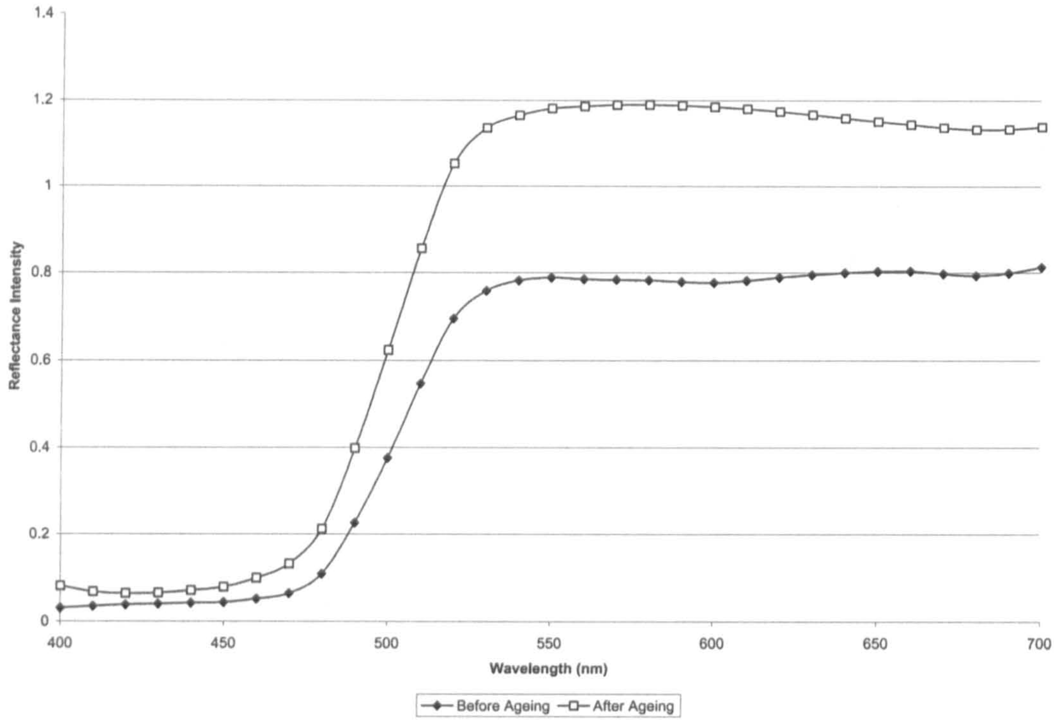
K.58 Plot showing the change in reflectance spectra of the black toner from the Canon CLBP 460PS ink set printed on Canon Ultra White paper (5.4) after exposure to daylight for 50,863 klux hours unfiltered.



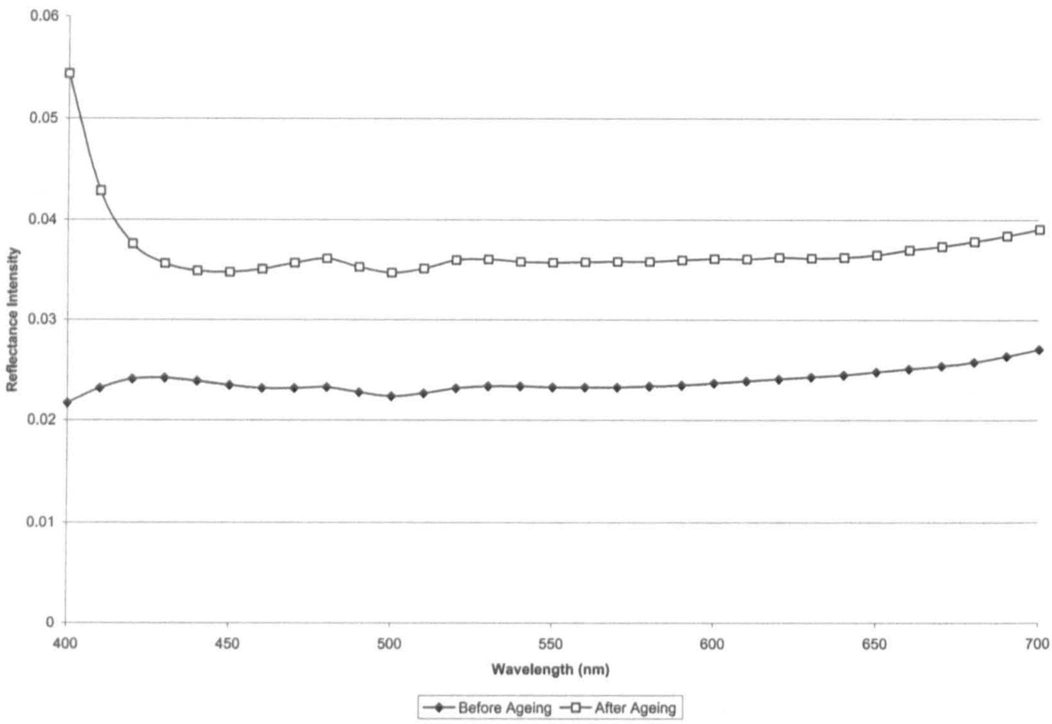
K.59 Plot showing the change in reflectance spectra of the cyan toner from the Canon CLBP 460PS ink set printed on Canon Card (5.5) after exposure to daylight for 50,863 klux hours unfiltered.



K.60 Plot showing the change in reflectance spectra of the magenta toner from the Canon CLBP 460PS ink set printed on Canon Card (5.5) after exposure to daylight for 50,863 klux hours unfiltered.

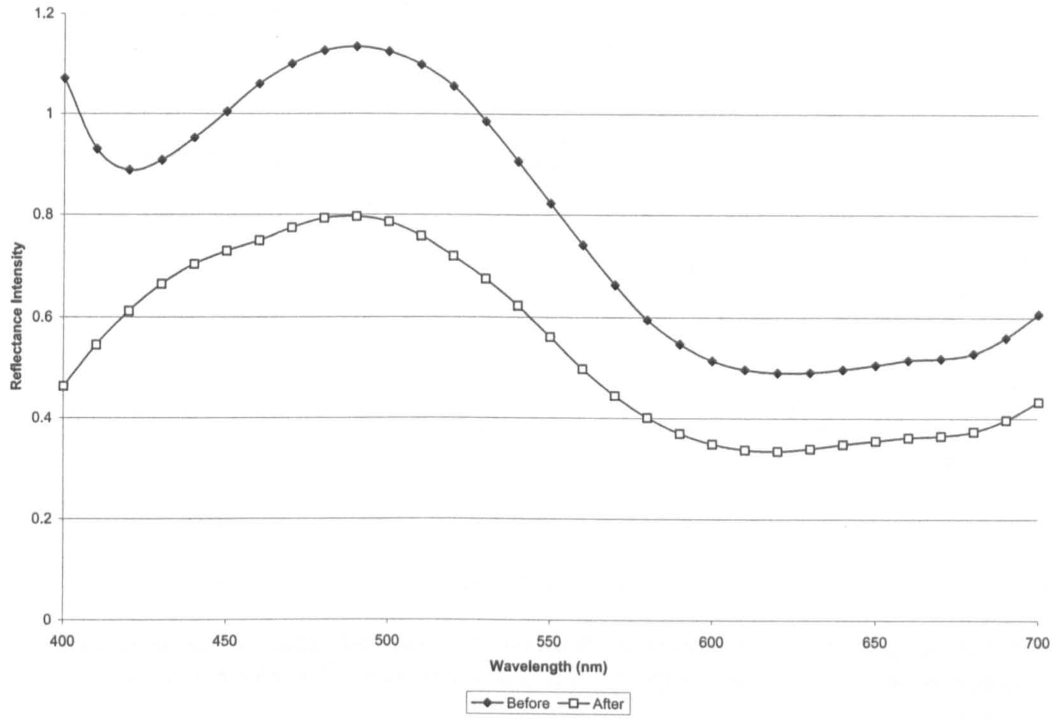


K.61 Plot showing the change in reflectance spectra of the yellow toner from the Canon CLBP 460PS ink set printed on Canon Card (5.5) after exposure to daylight for 50,863 klux hours unfiltered.

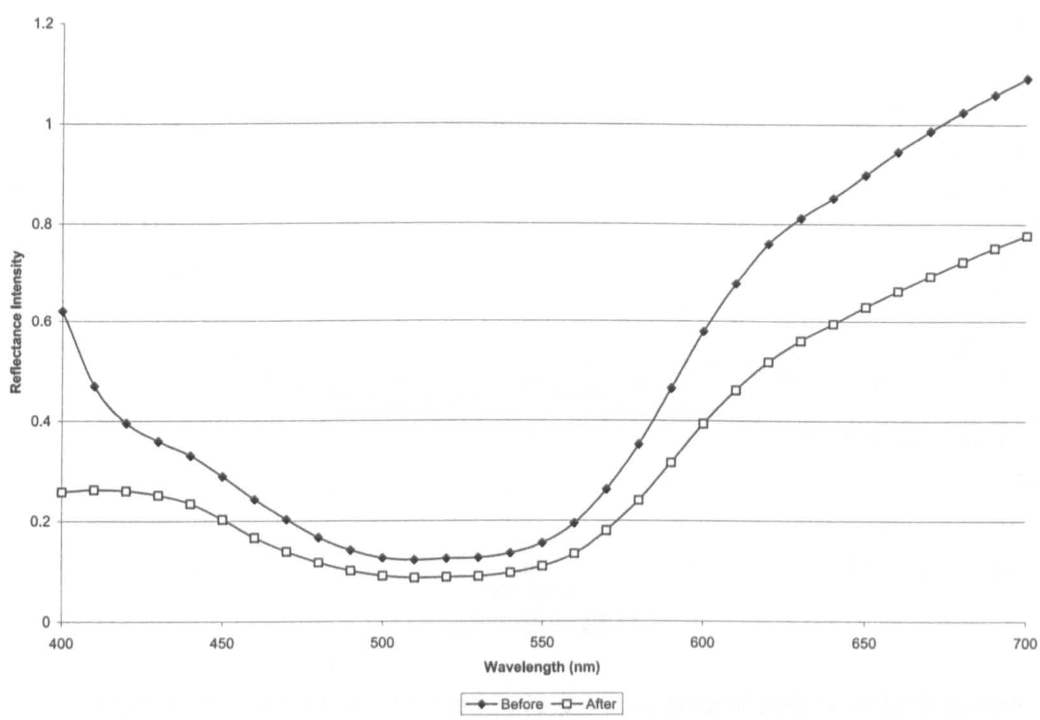


K.62 Plot showing the change in reflectance spectra of the black toner from the Canon CLBP 460PS ink set printed on Canon Card (5.5) after exposure to daylight for 50,863 klux hours unfiltered.

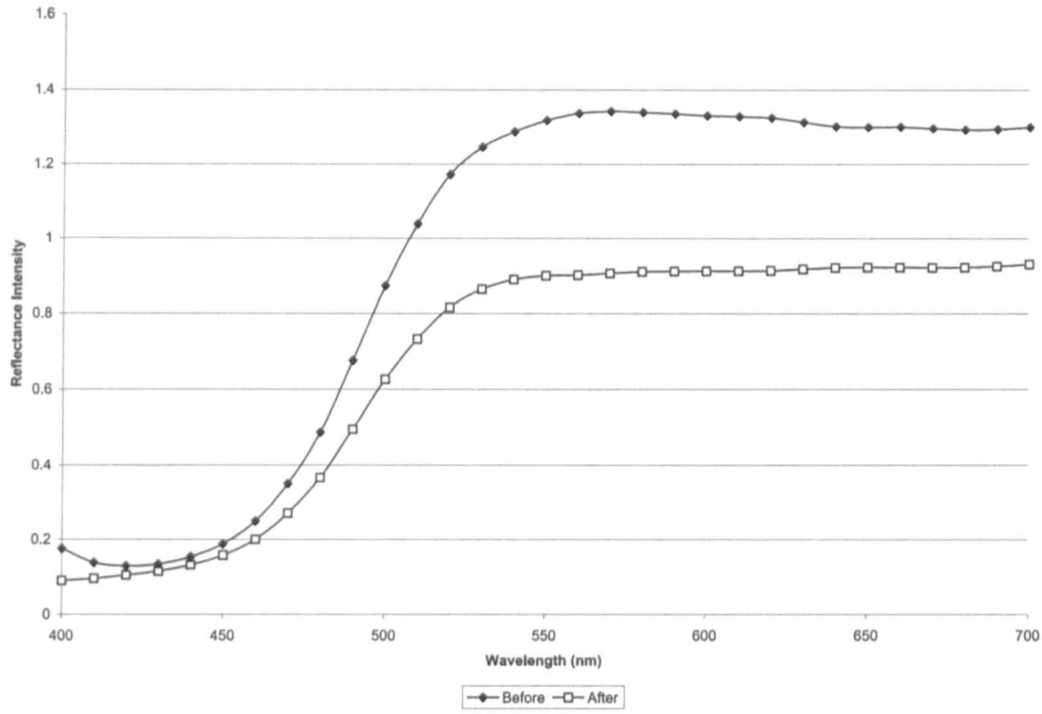
APPENDIX L -Spectral reflectance curves for the samples exposed to the fluorescent light fastness tester with UV filters



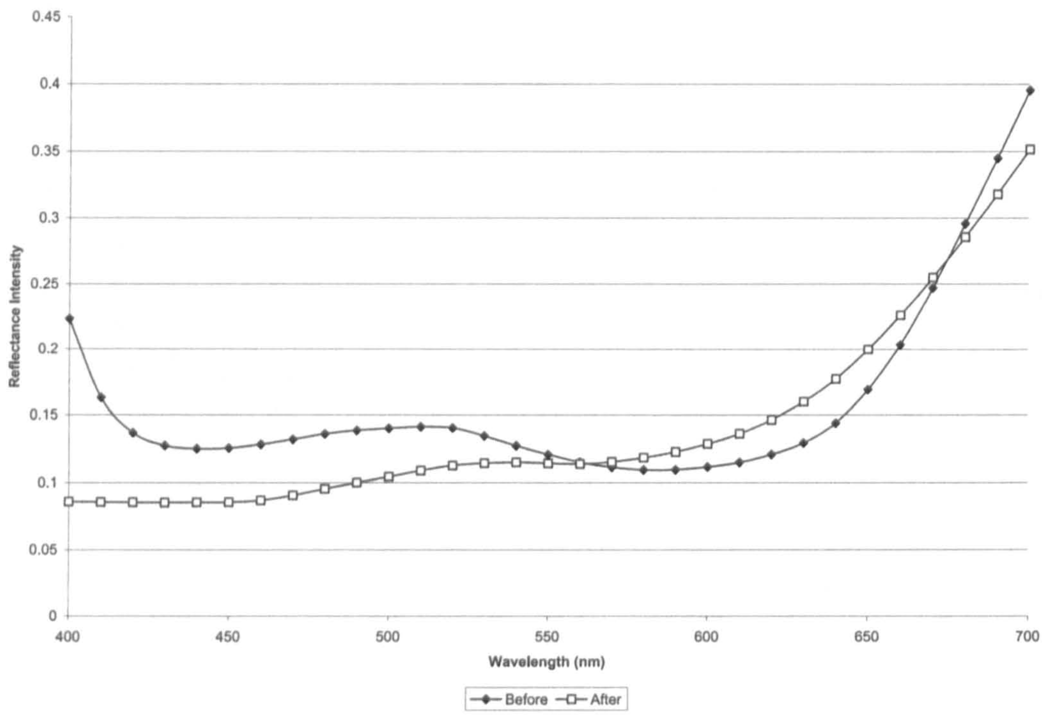
L.1 Plot showing the change in reflectance spectra of the cyan ink from the Iris Morgan FA ink set printed on Somerset Velvet paper (1.1) after exposure to the fluorescent light tester with an UV filter.



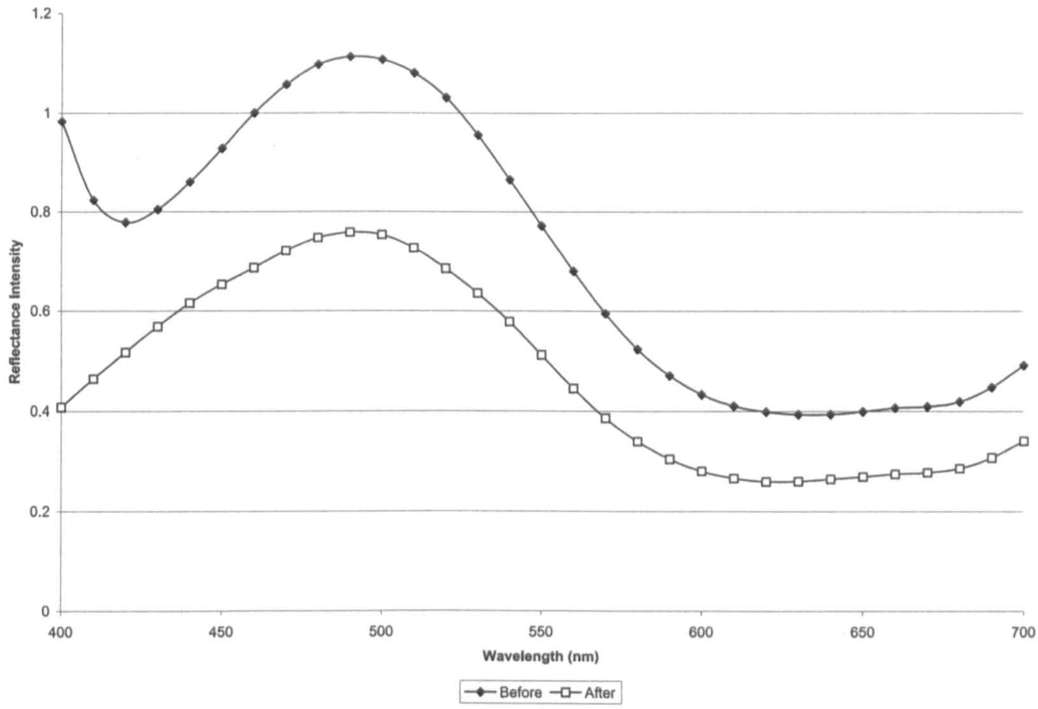
L.2 Plot showing the change in reflectance spectra of the magenta ink from the Iris Morgan FA ink set printed on Somerset Velvet paper (1.1) after exposure to the fluorescent light tester with an UV filter.



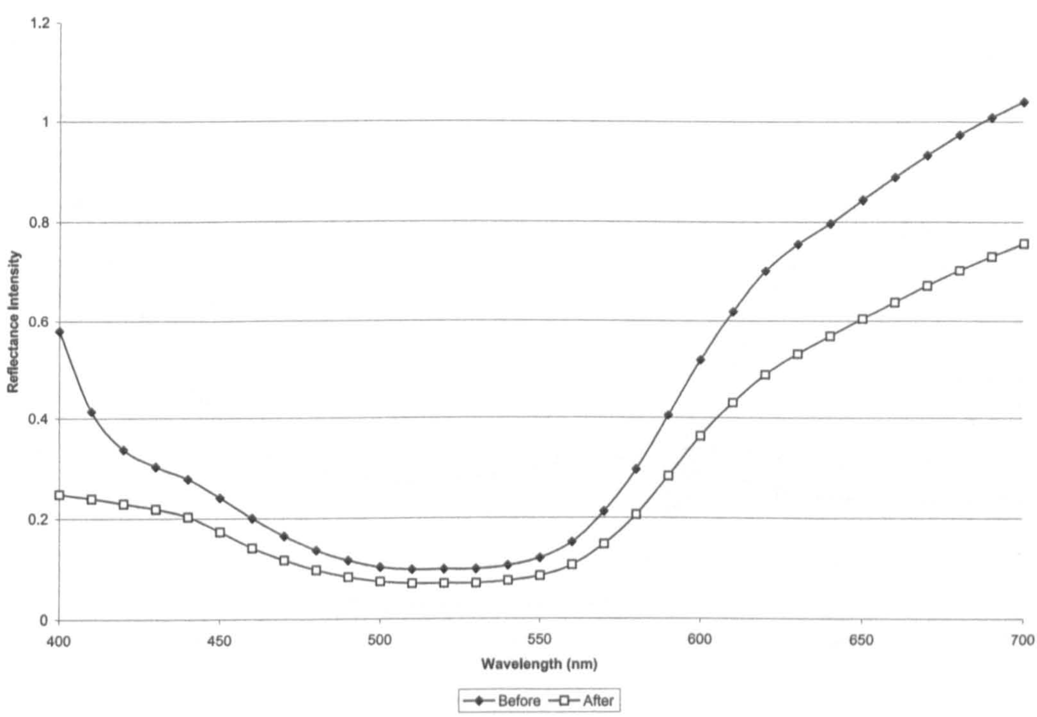
L.3 Plot showing the change in reflectance spectra of the yellow ink from the Iris Morgan FA ink set printed on Somerset Velvet paper (1.1) after exposure to the fluorescent light tester with an UV filter.



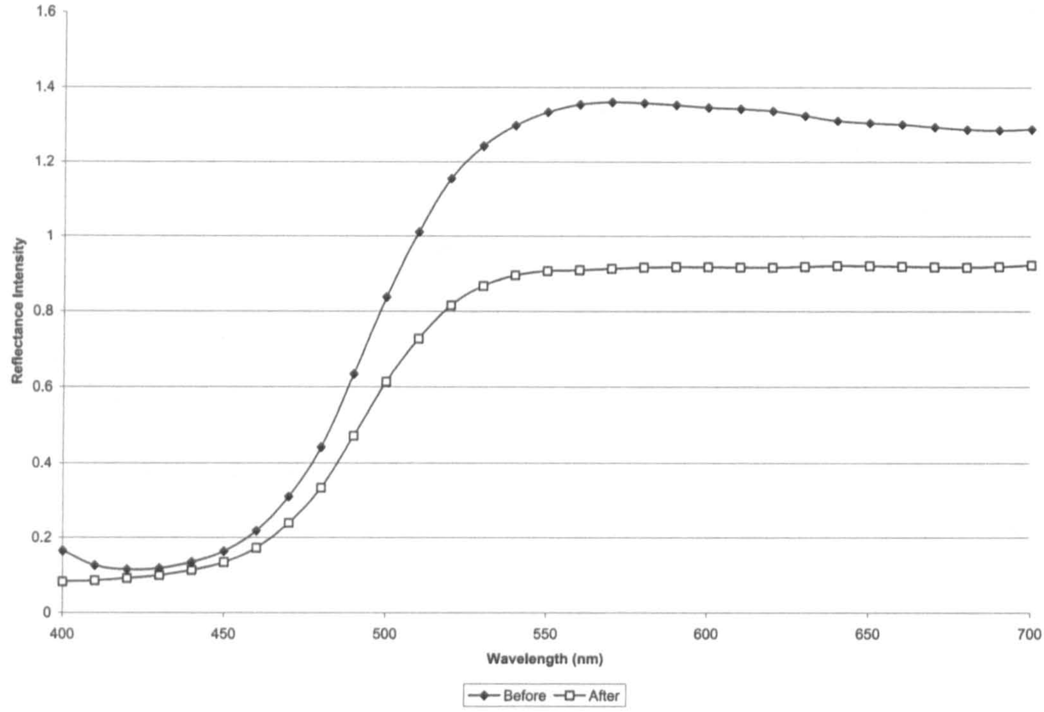
L.4 Plot showing the change in reflectance spectra of the black ink from the Iris Morgan FA ink set printed on Somerset Velvet paper (1.1) after exposure to the fluorescent light tester with an UV filter.



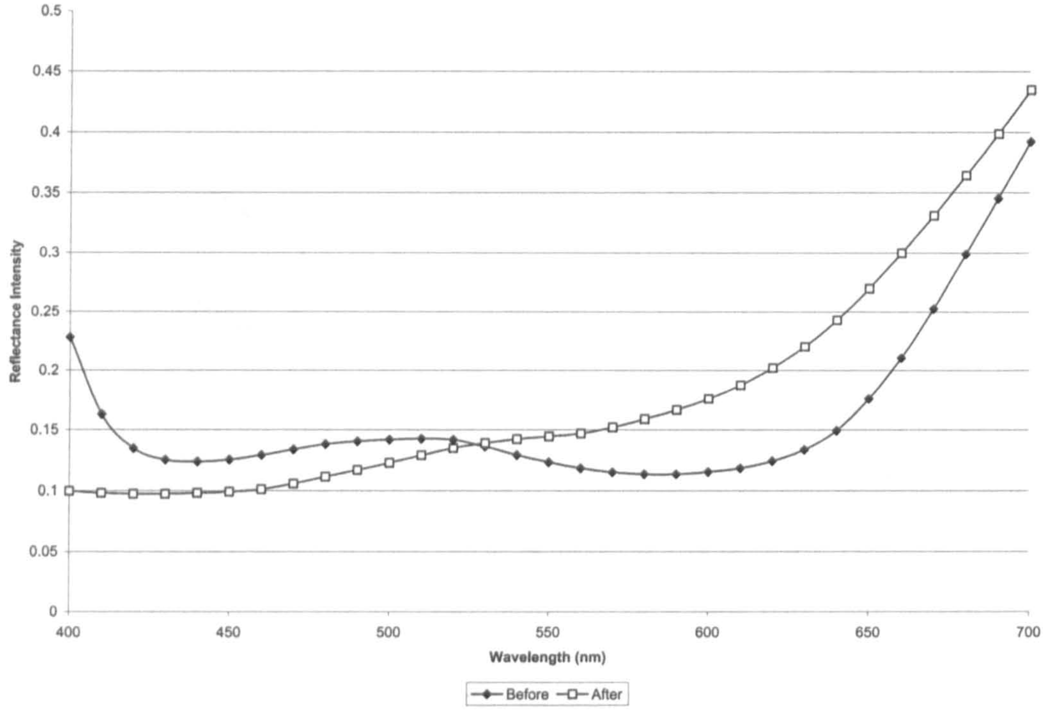
L.5 Plot showing the change in reflectance spectra of the cyan ink from the Iris Morgan FA ink set printed on Whatman paper (1.2) after exposure to the fluorescent light tester with an UV filter.



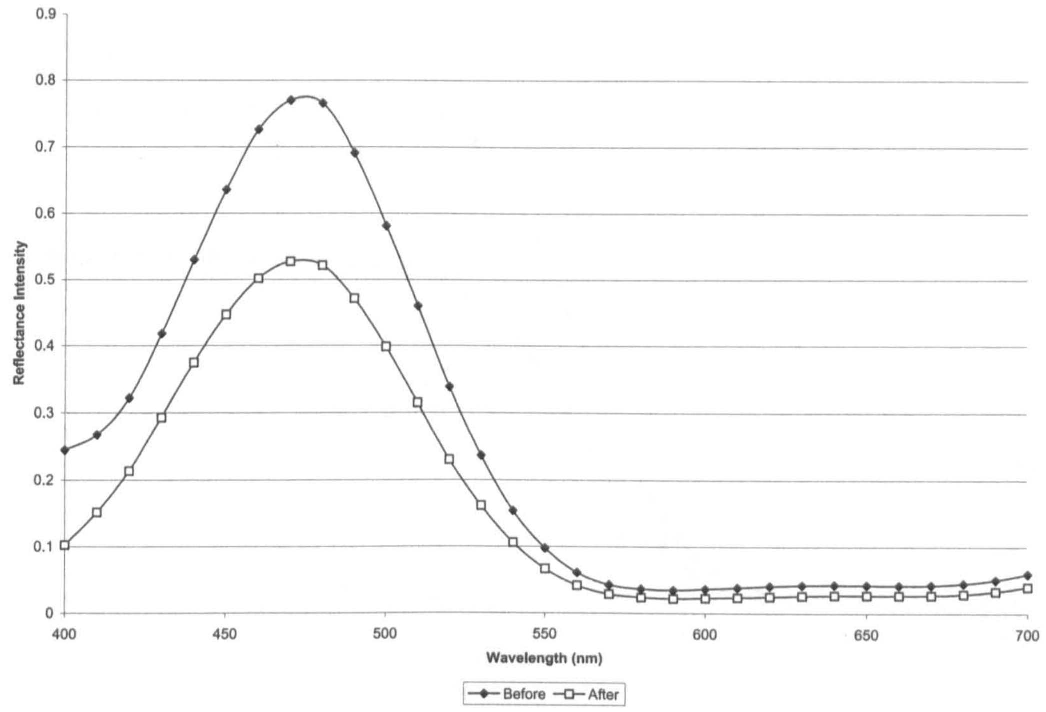
L.6 Plot showing the change in reflectance spectra of the magenta ink from the Iris Morgan FA ink set printed on Whatman paper (1.2) after exposure to the fluorescent light tester with an UV filter.



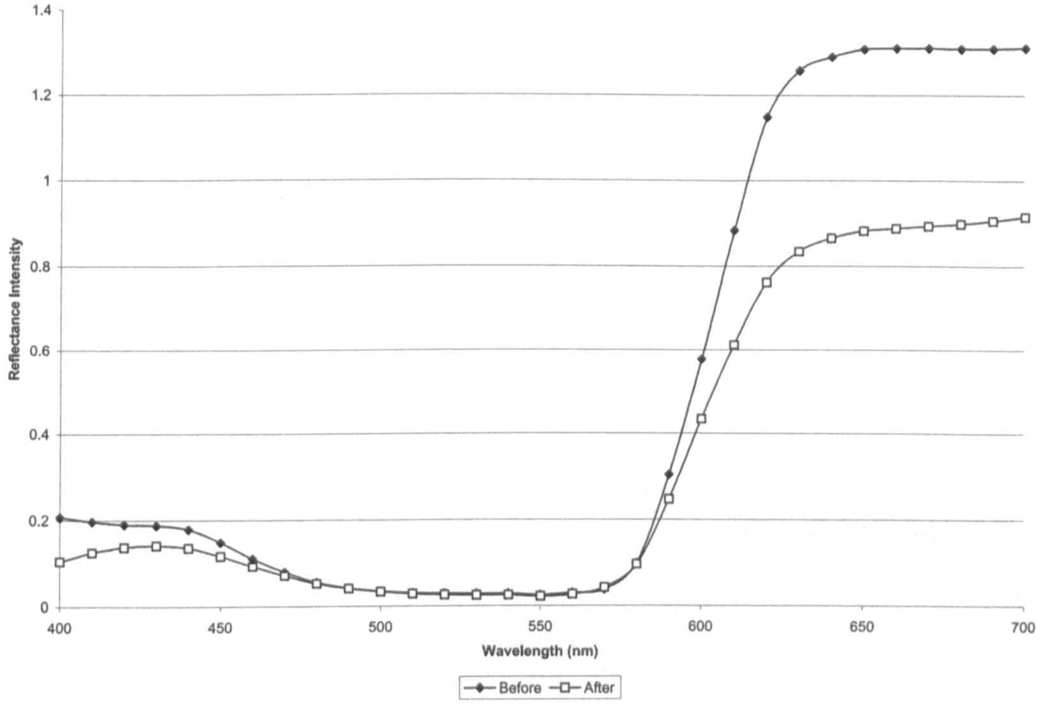
L.7 Plot showing the change in reflectance spectra of the yellow ink from the Iris Morgan FA ink set printed on Whatman paper (1.2) after exposure to the fluorescent light tester with an UV filter.



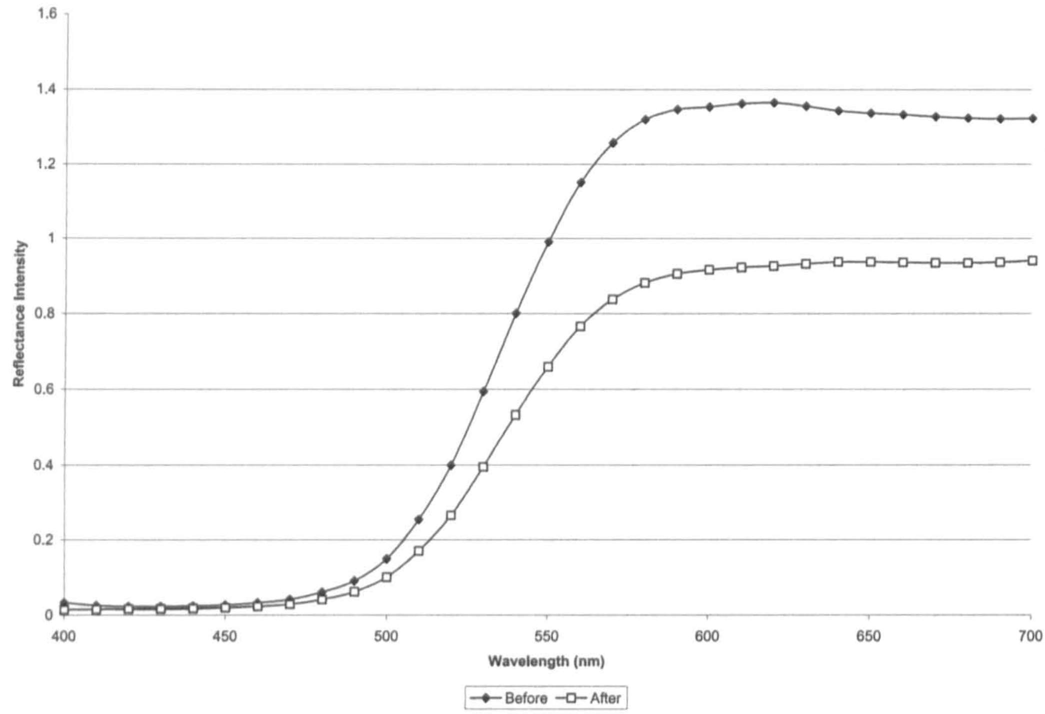
L.8 Plot showing the change in reflectance spectra of the black ink from the Iris Morgan FA ink set printed on Whatman paper (1.2) after exposure to the fluorescent light tester with an UV filter.



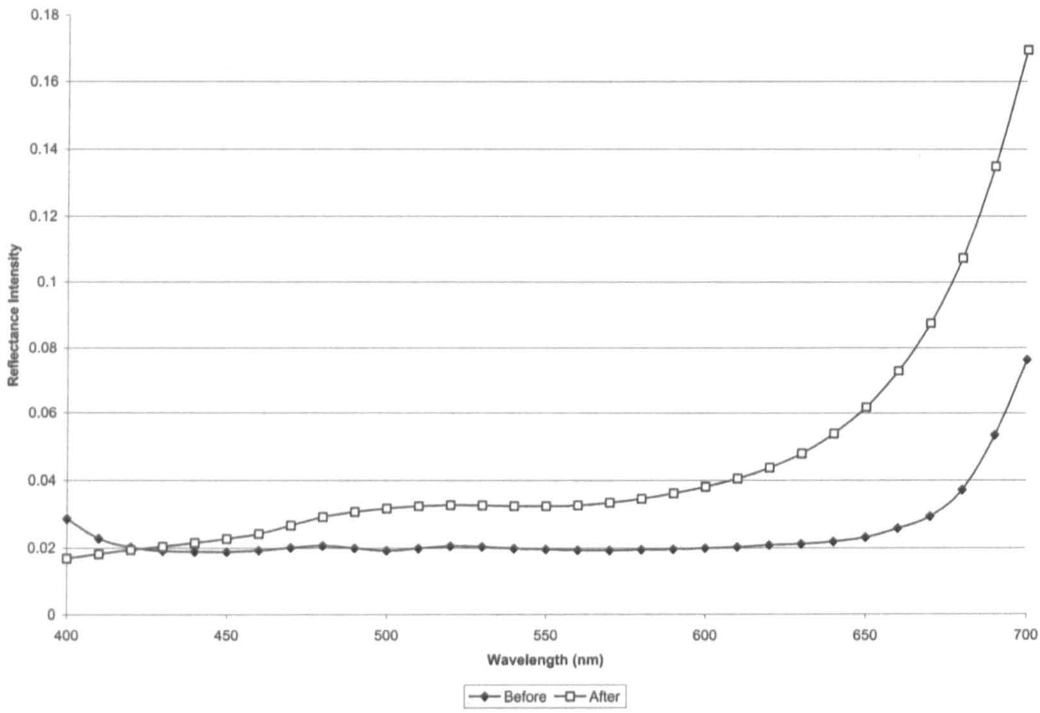
L.9 Plot showing the change in reflectance spectra of the cyan ink from the Epson Pro 9000 ink set printed on the ISVE paper (3.2) after exposure to the fluorescent light tester with an UV filter.



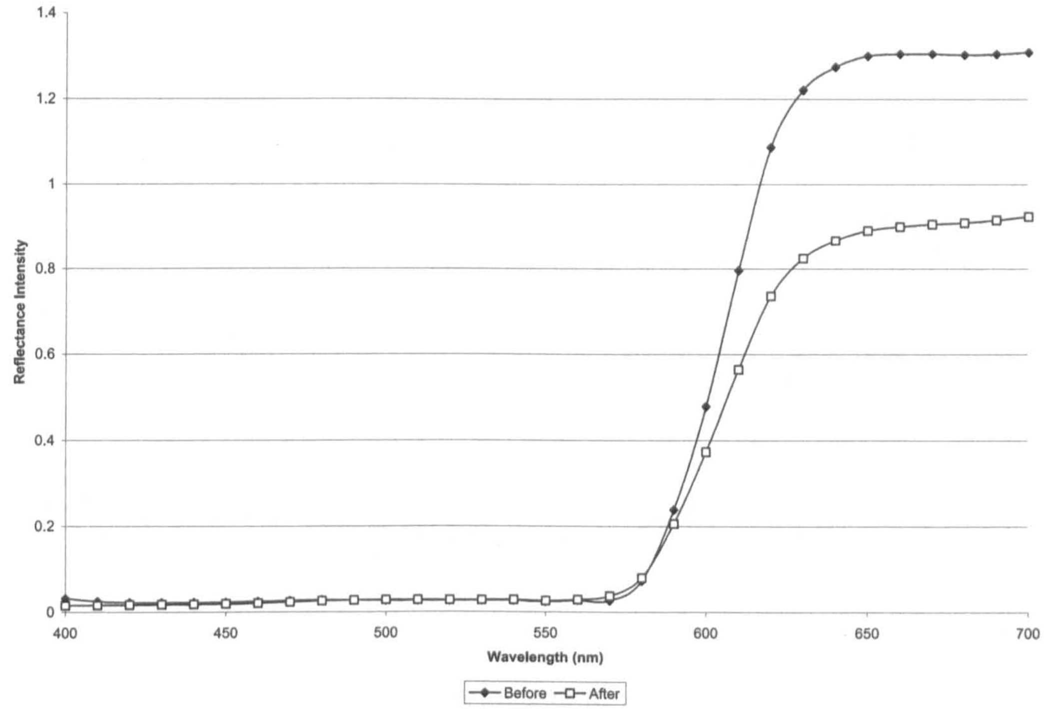
L.10 Plot showing the change in reflectance spectra of the magenta ink from the Epson Pro 9000 ink set printed on the ISVE paper (3.2) after exposure to the fluorescent light tester with an UV filter.



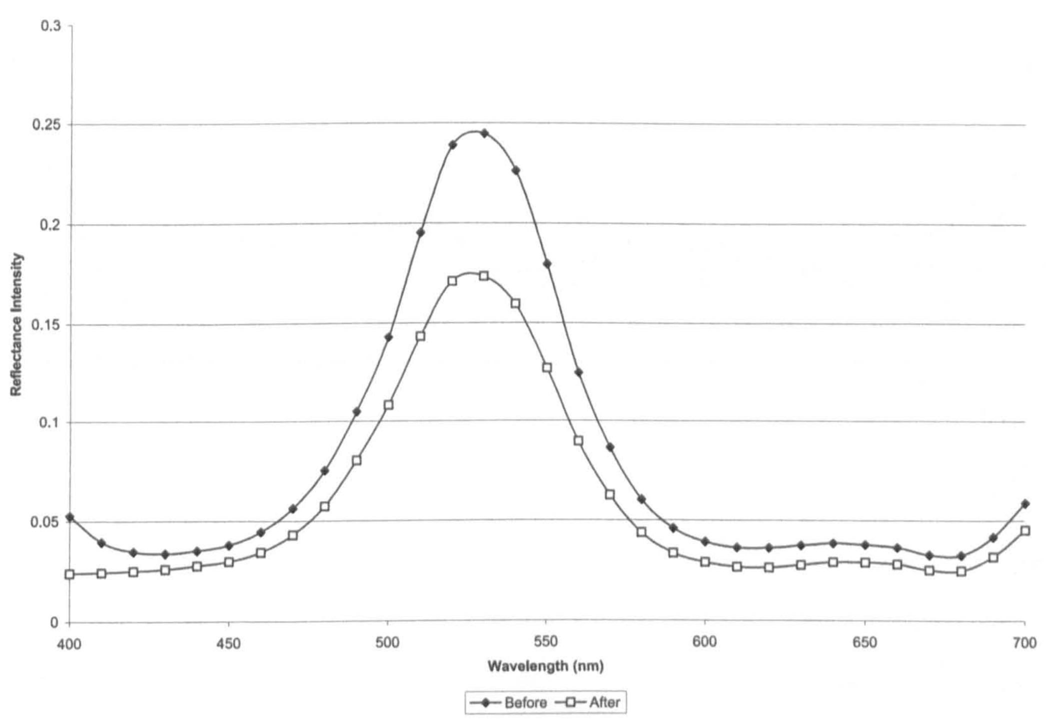
L.11 Plot showing the change in reflectance spectra of the yellow ink from the Epson Pro 9000 ink set printed on the ISVE paper (3.2) after exposure to the fluorescent light tester with an UV filter.



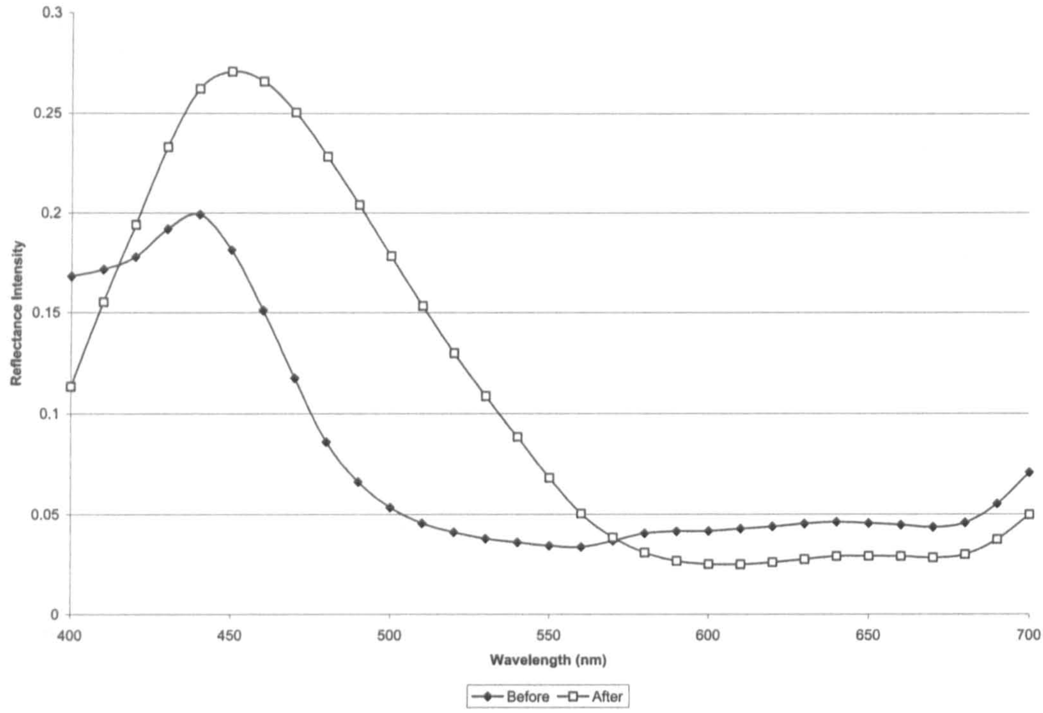
L.12 Plot showing the change in reflectance spectra of the black ink from the Epson Pro 9000 ink set printed on the ISVE paper (3.2) after exposure to the fluorescent light tester with an UV filter.



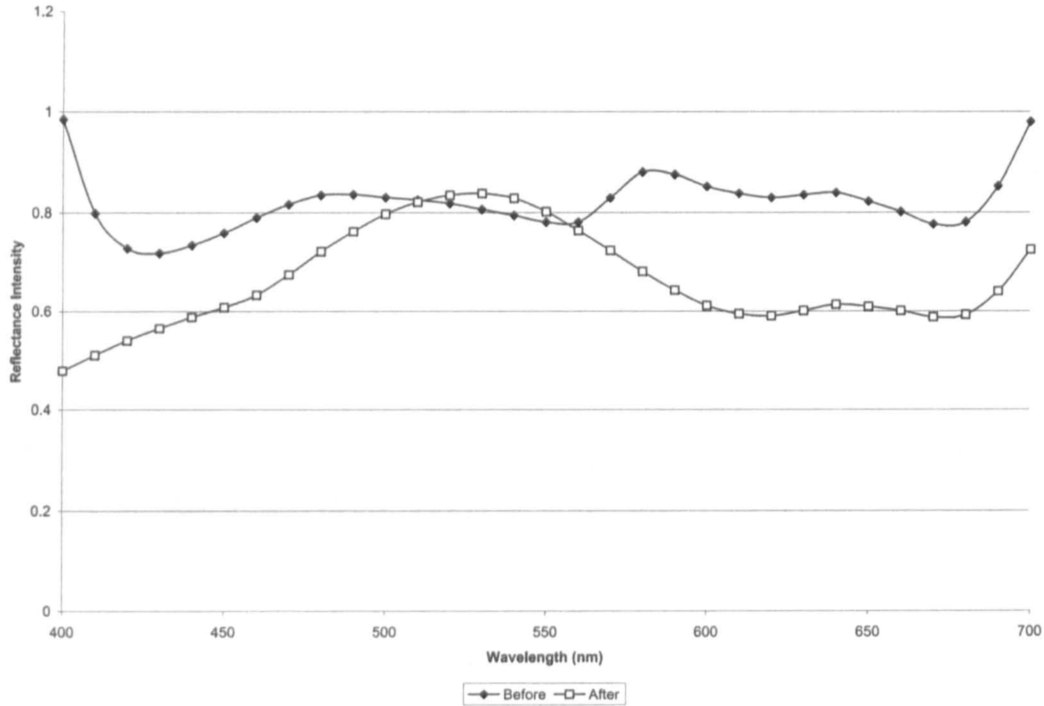
L.13 Plot showing the change in reflectance spectra of the red ink patch from the Epson Pro 9000 ink set printed on the ISVE paper (3.2) after exposure to the fluorescent light tester with an UV filter.



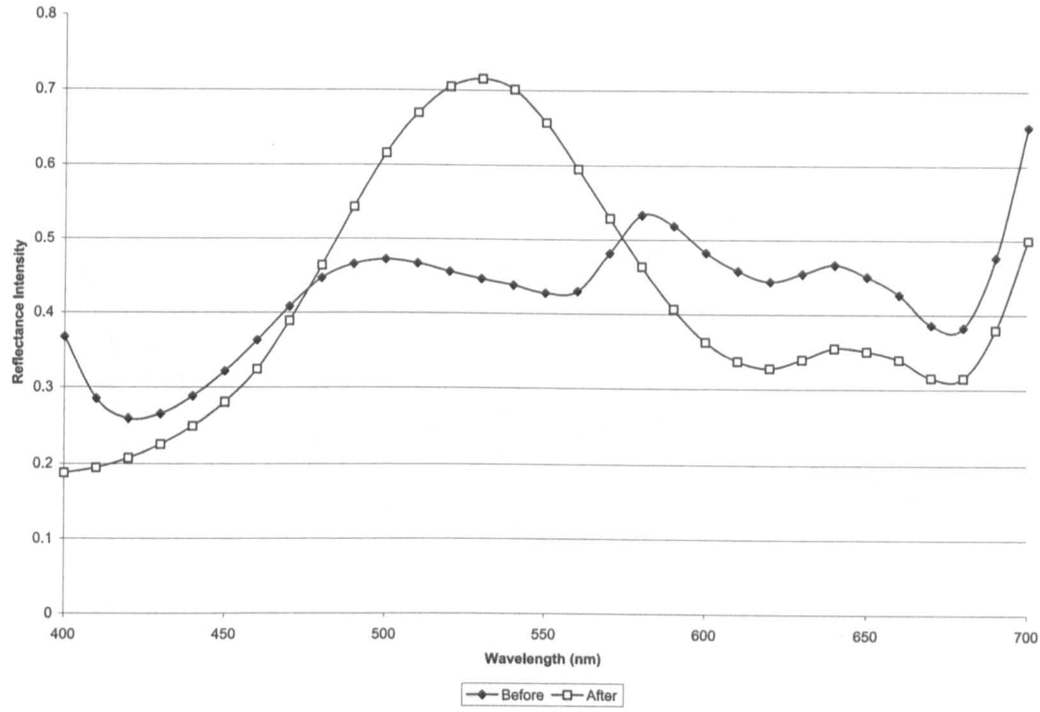
L.14 Plot showing the change in reflectance spectra of the green ink patch from the Epson Pro 9000 ink set printed on the ISVE paper (3.2) after exposure to the fluorescent light tester with an UV filter.



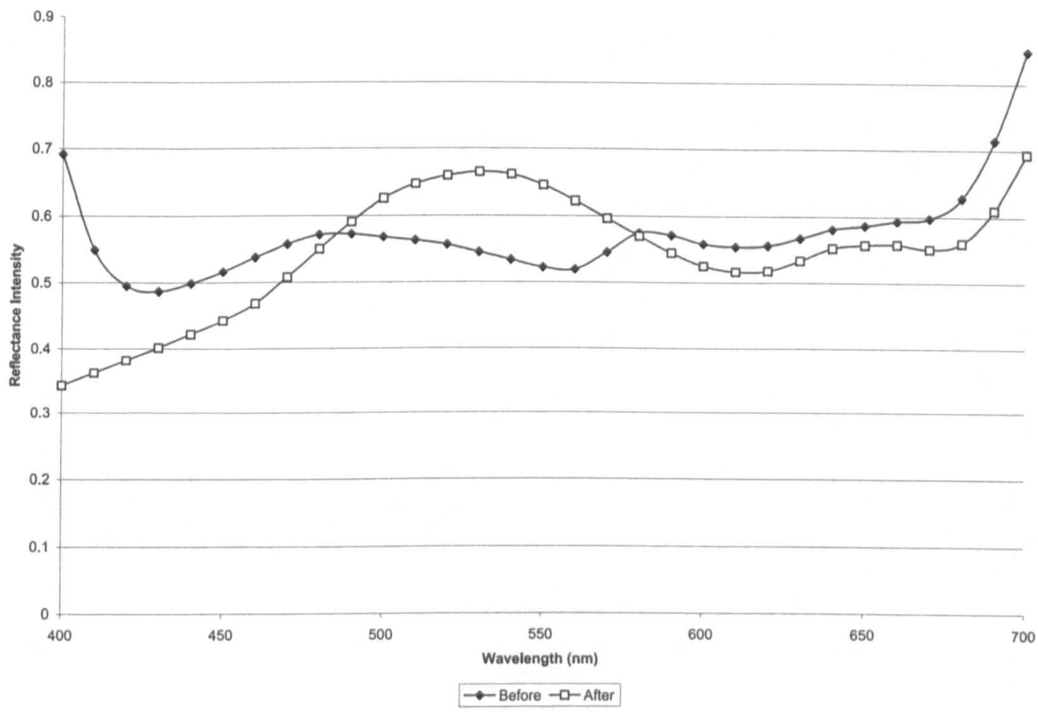
L.15 Plot showing the change in reflectance spectra of the blue ink patch from the Epson Pro 9000 ink set printed on the ISVE paper (3.2) after exposure to the fluorescent light tester with an UV filter.



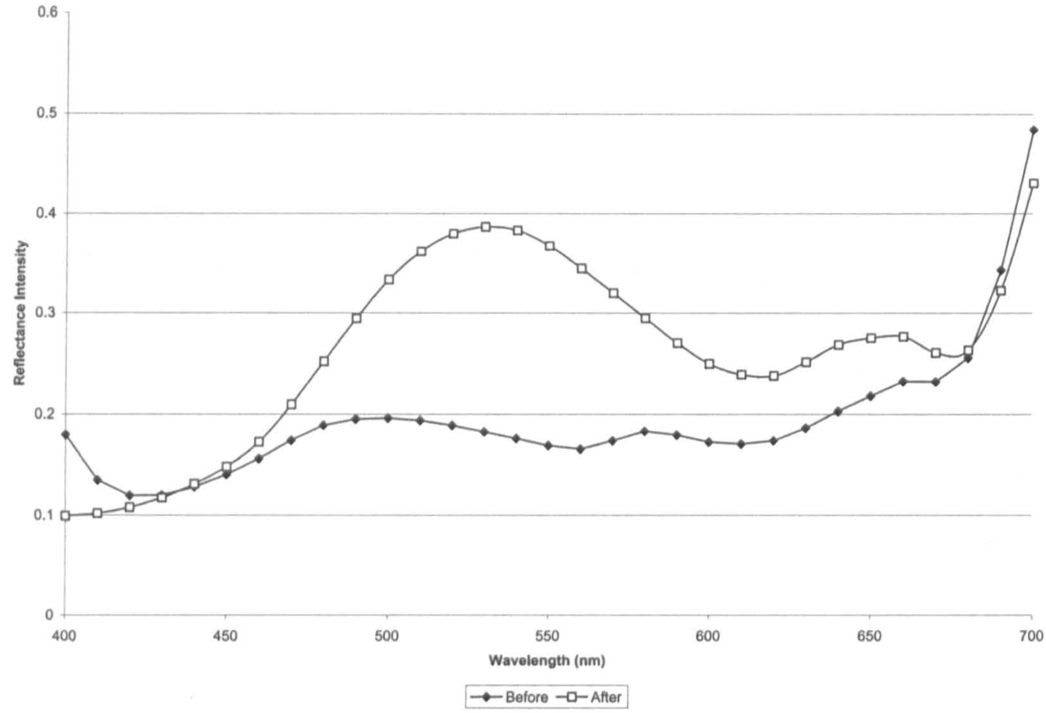
L.16 Plot showing the change in reflectance spectra of the 25 % CMY ink patch from the Epson Pro 9000 ink set printed on the ISVE paper (3.2) after exposure to the fluorescent light tester with an UV filter.



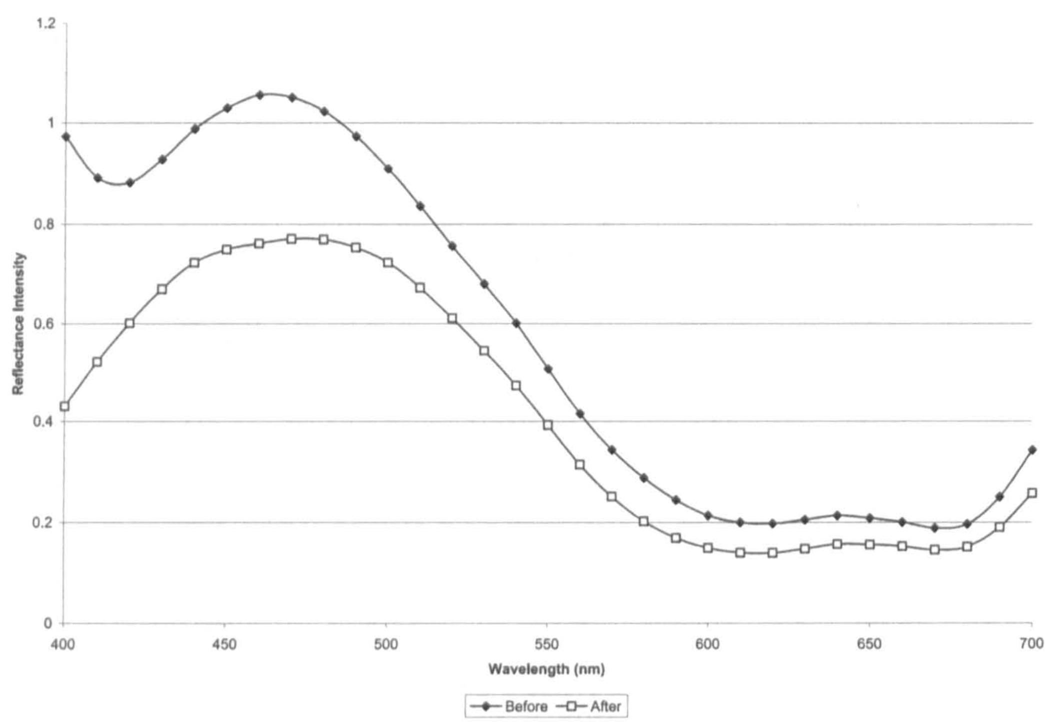
L.17 Plot showing the change in reflectance spectra of the 50 % CMY ink patch from the Epson Pro 9000 ink set printed on the ISVE paper (3.2) after exposure to the fluorescent light tester with an UV filter.



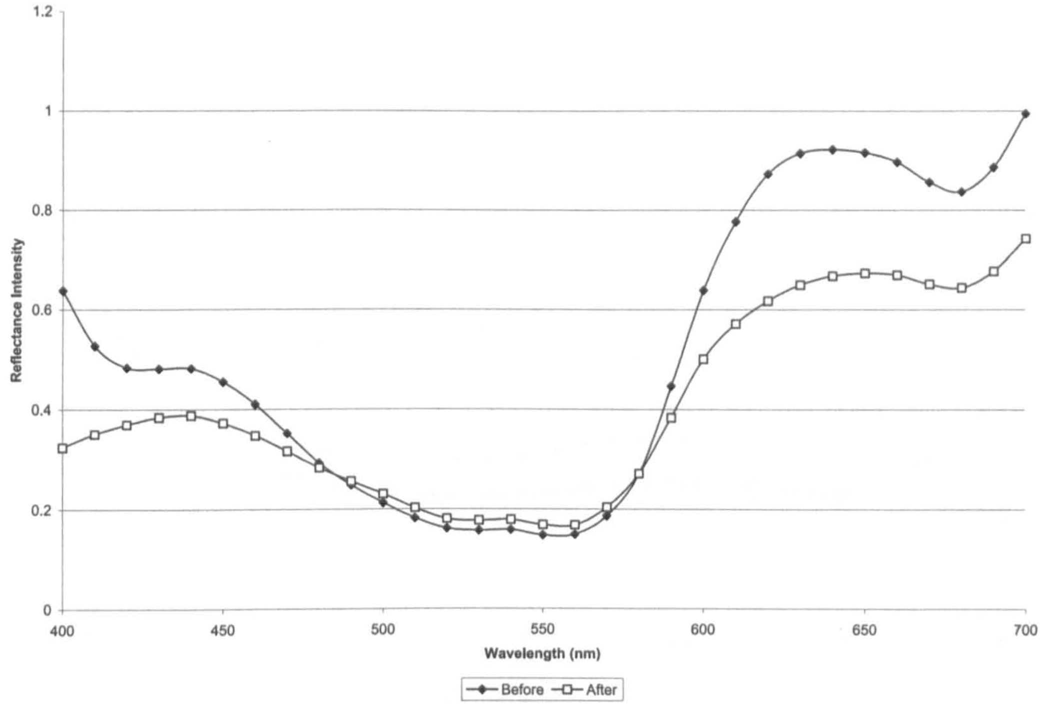
L.18 Plot showing the change in reflectance spectra of the 25 % CMYK ink patch from the Epson Pro 9000 ink set printed on the Somerset Velvet paper (3.3) after exposure to the fluorescent light tester with an UV filter.



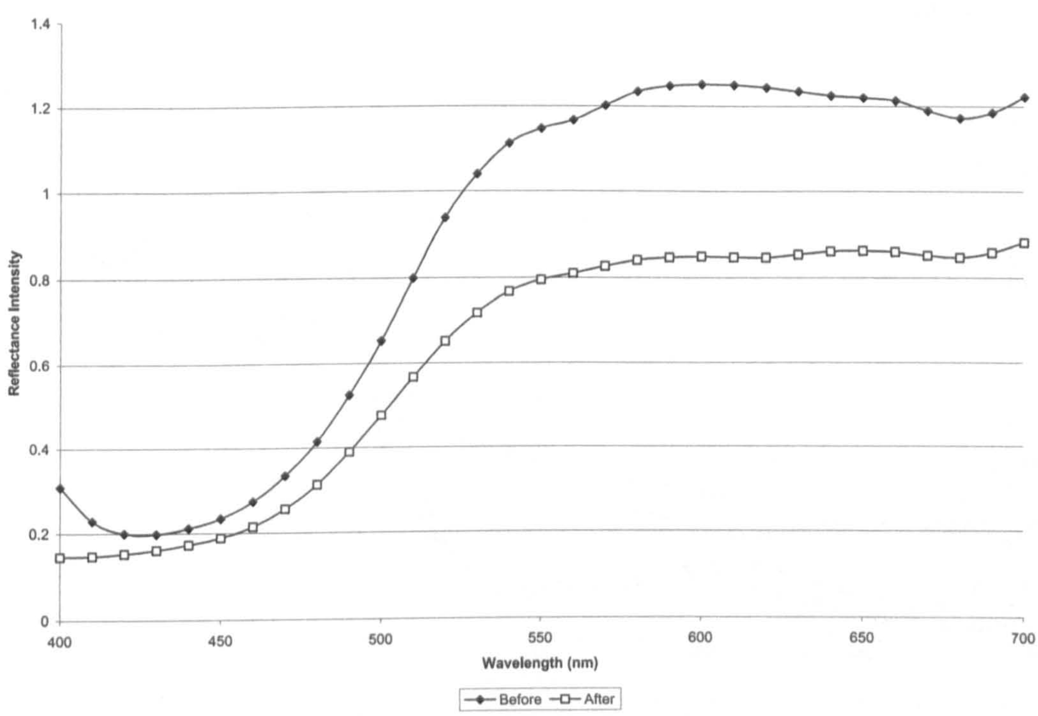
L.19 Plot showing the change in reflectance spectra of the 50 % CMYK ink patch from the Epson Pro 9000 ink set printed on the Somerset Velvet paper (3.3) after exposure to the fluorescent light tester with an UV filter.



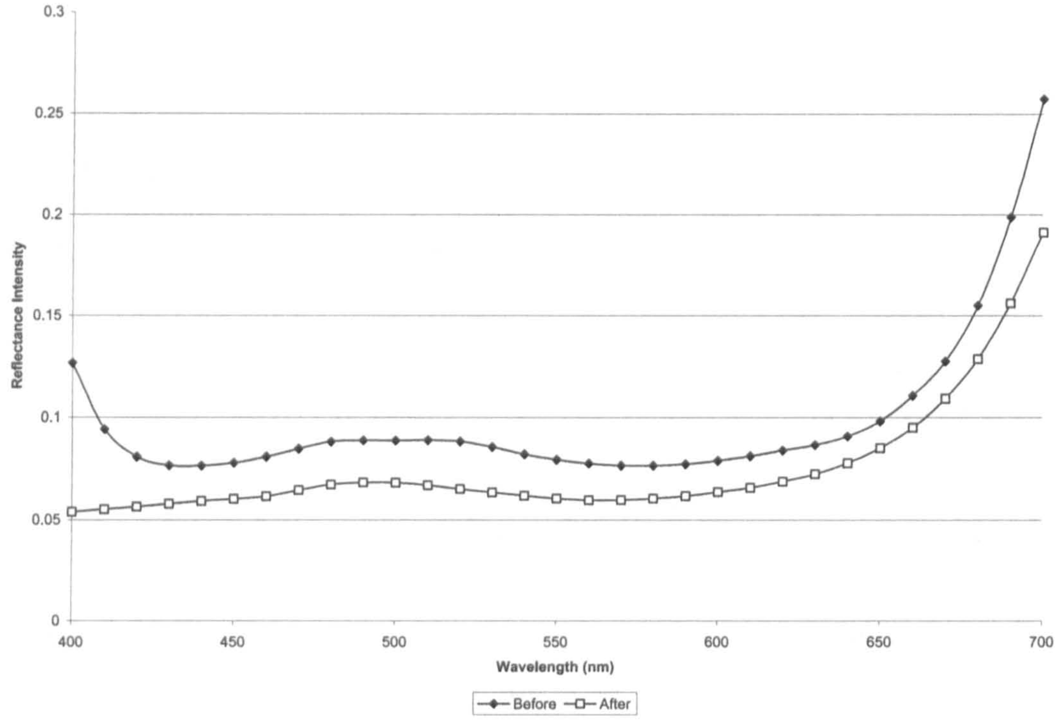
L.20 Plot showing the change in reflectance spectra of the cyan ink from the Epson Pro 9000 ink set printed on the Somerset Velvet paper (3.3) after exposure to the fluorescent light tester with an UV filter.



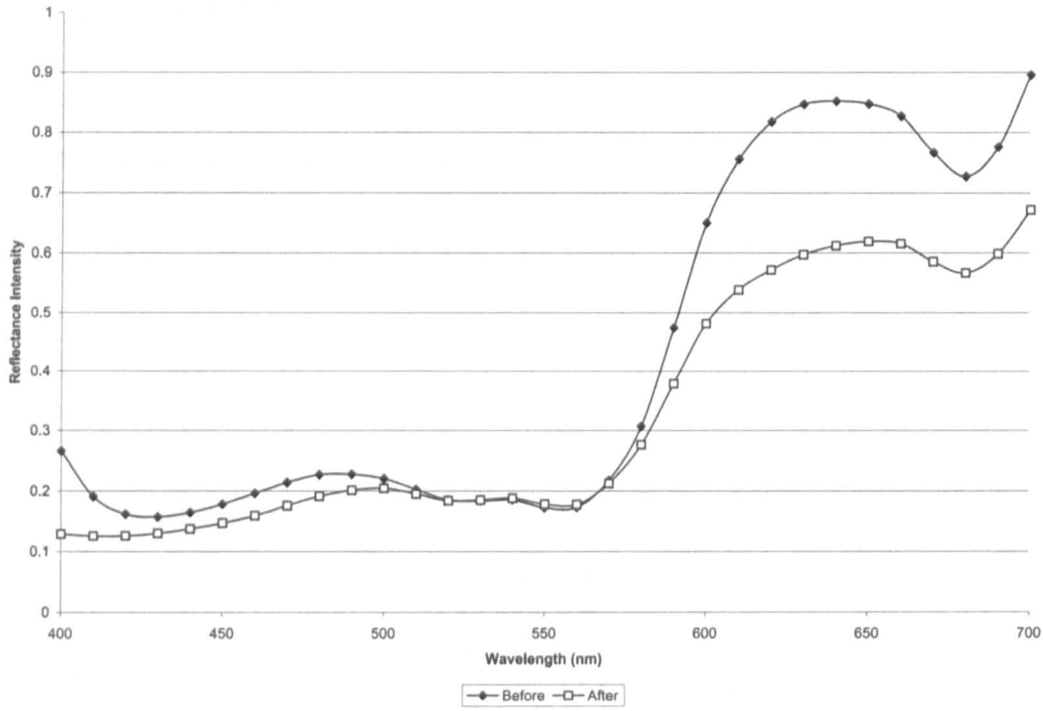
L.21 Plot showing the change in reflectance spectra of the magenta ink from the Epson Pro 9000 ink set printed on the Somerset Velvet paper (3.3) after exposure to the fluorescent light tester with an UV filter.



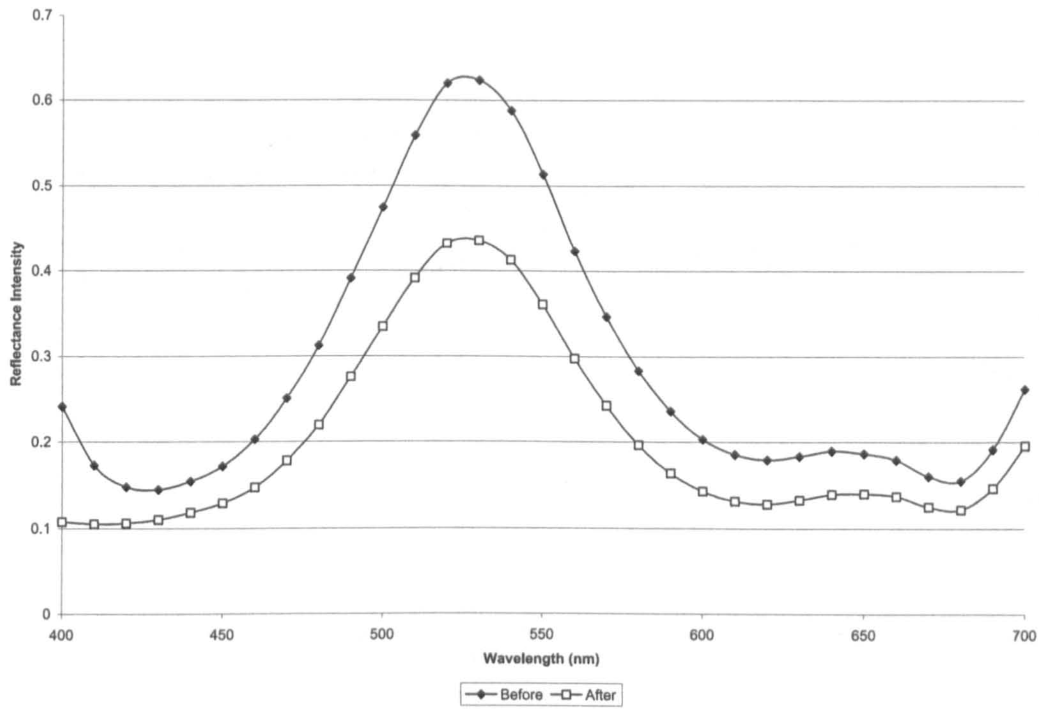
L.22 Plot showing the change in reflectance spectra of the yellow ink from the Epson Pro 9000 ink set printed on the Somerset Velvet paper (3.3) after exposure to the fluorescent light tester with an UV filter.



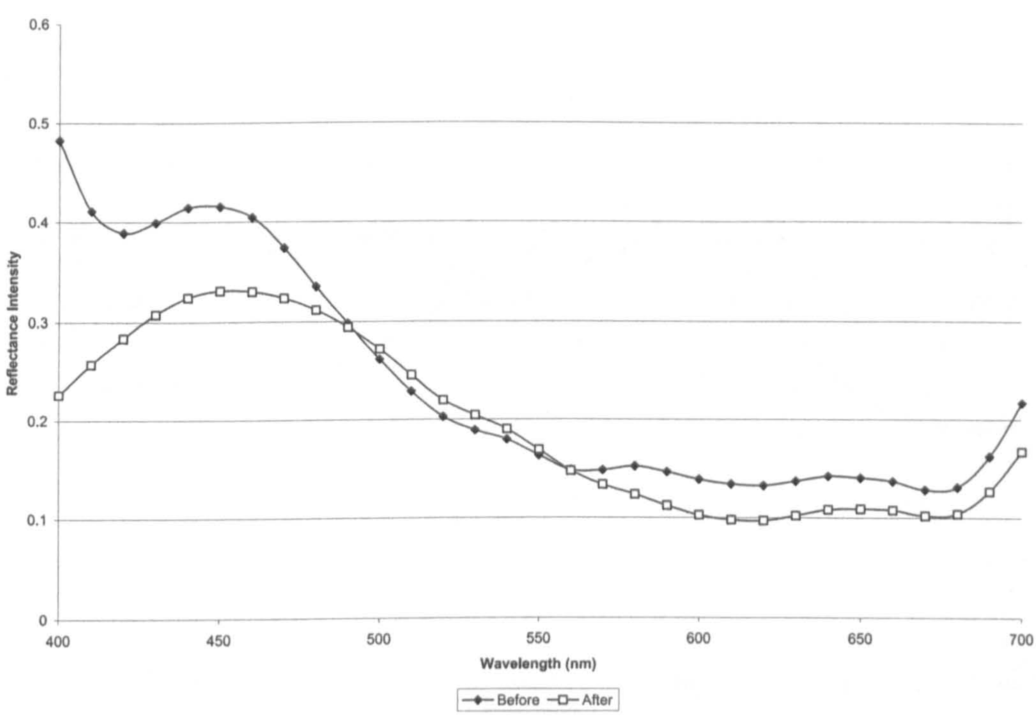
L.23 Plot showing the change in reflectance spectra of the black ink from the Epson Pro 9000 ink set printed on the Somerset Velvet paper (3.3) after exposure to the fluorescent light tester with an UV filter.



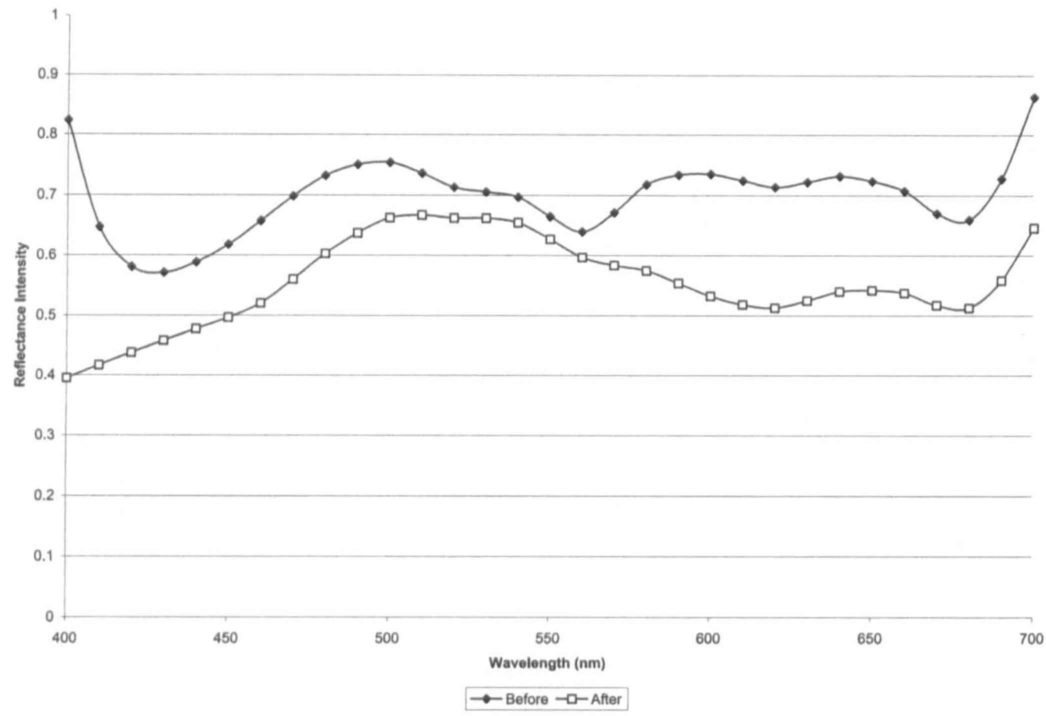
L.24 Plot showing the change in reflectance spectra of the red ink patch from the Epson Pro 9000 ink set printed on the Somerset Velvet paper (3.3) after exposure to the fluorescent light tester with an UV filter.



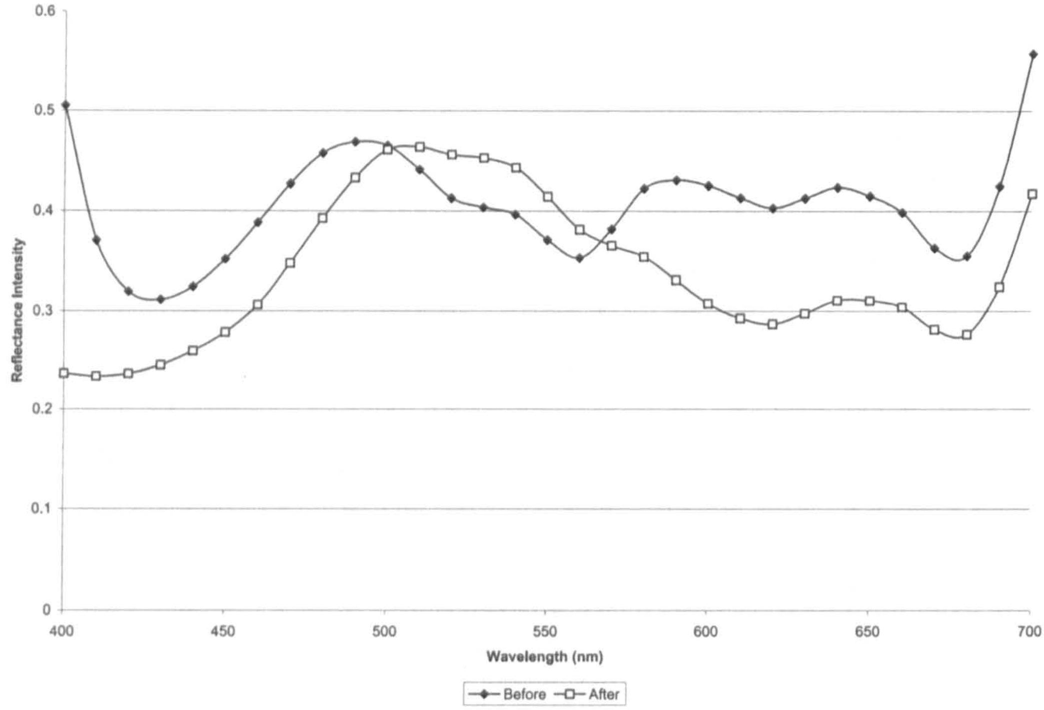
L.25 Plot showing the change in reflectance spectra of the green ink patch from the Epson Pro 9000 ink set printed on the Somerset Velvet paper (3.3) after exposure to the fluorescent light tester with an UV filter.



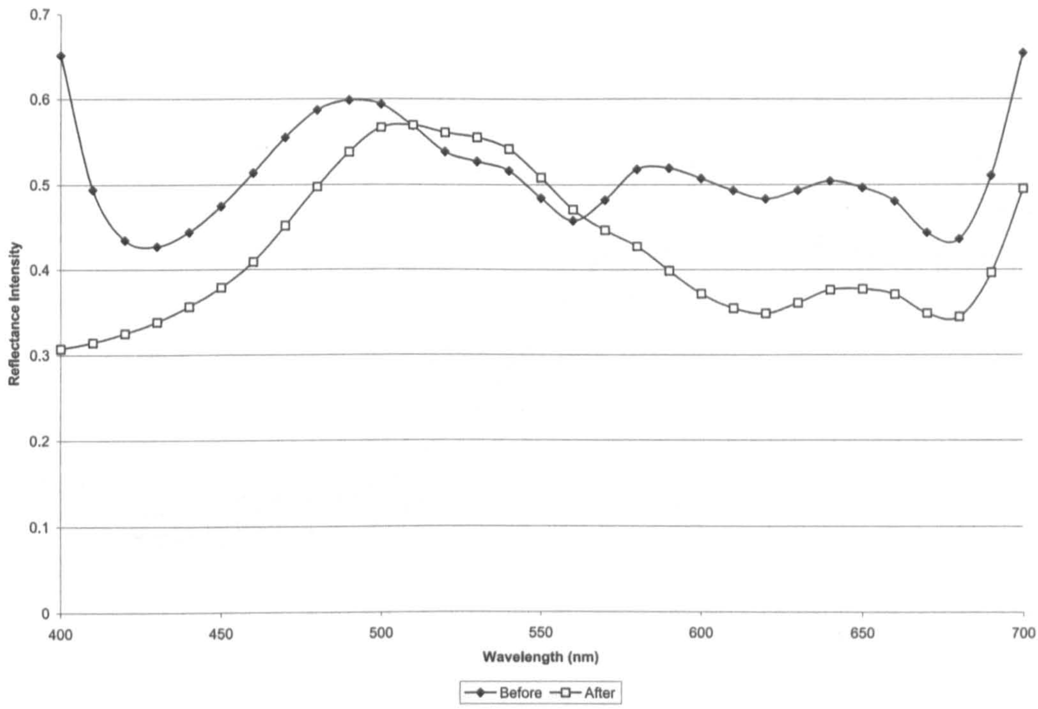
L.26 Plot showing the change in reflectance spectra of the blue ink patch from the Epson Pro 9000 ink set printed on the Somerset Velvet paper (3.3) after exposure to the fluorescent light tester with an UV filter.



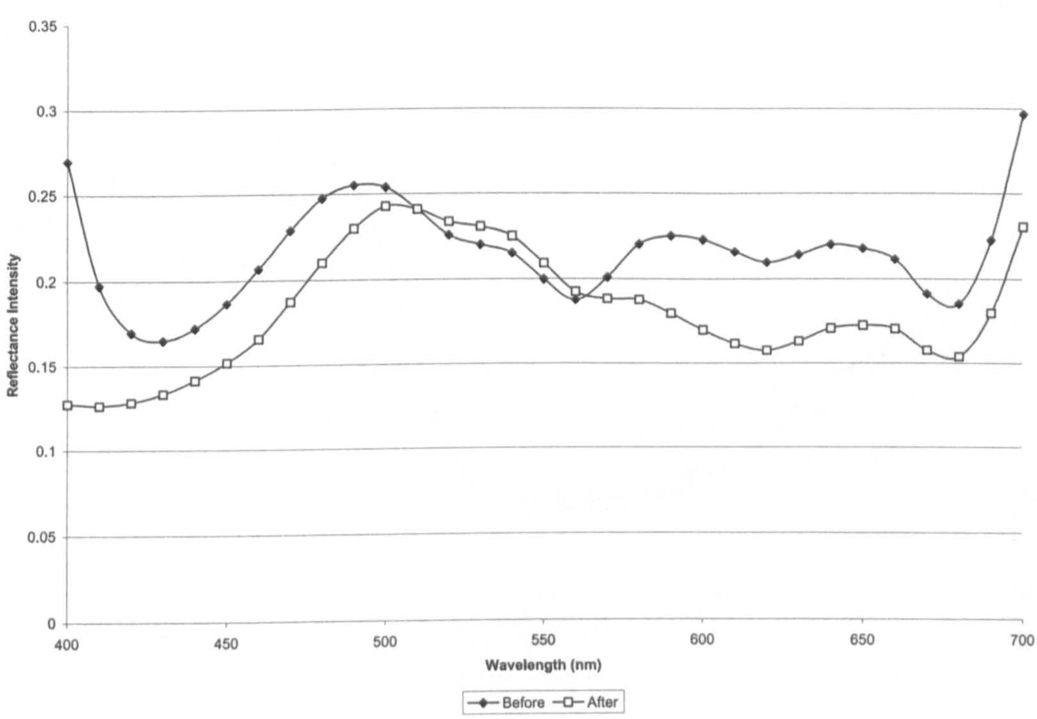
L.27 Plot showing the change in reflectance spectra of the 25 % CMY ink patch from the Epson Pro 9000 ink set printed on the Somerset Velvet paper (3.3) after exposure to the fluorescent light tester with an UV filter.



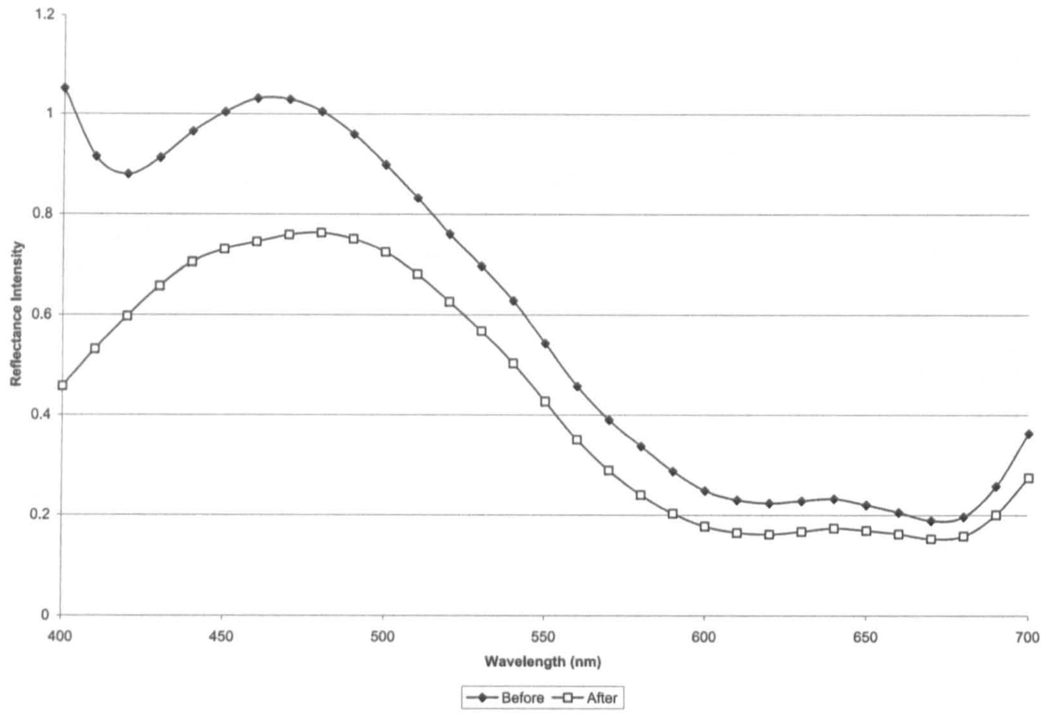
L.28 Plot showing the change in reflectance spectra of the 50 % CMY ink patch from the Epson Pro 9000 ink set printed on the Somerset Velvet paper (3.3) after exposure to the fluorescent light tester with an UV filter.



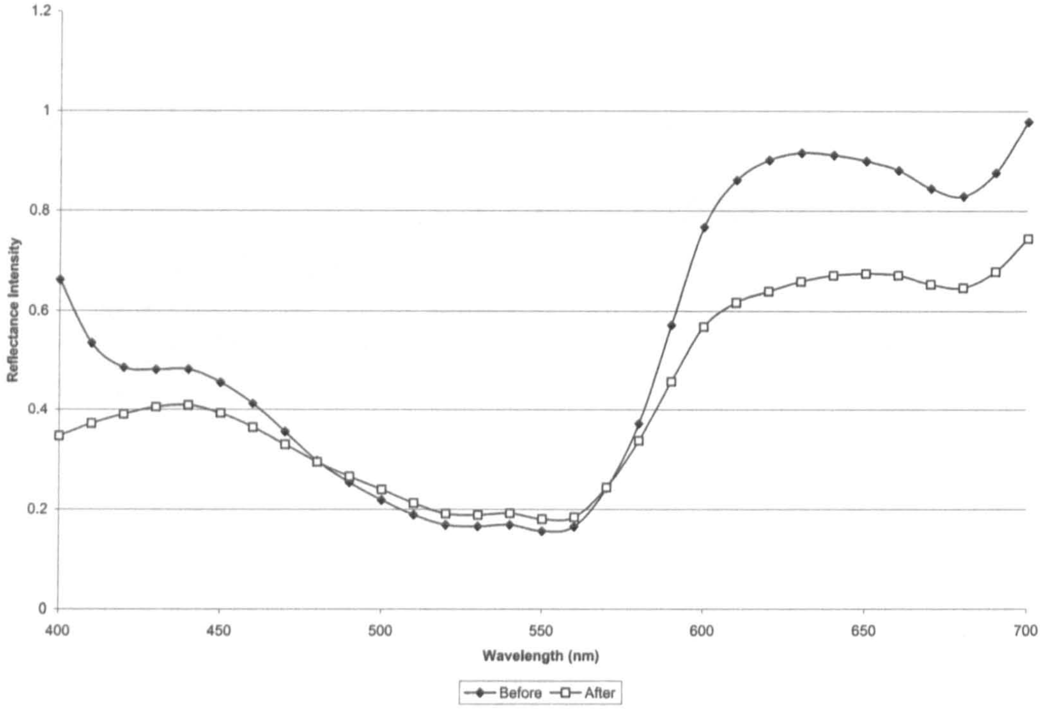
L.29 Plot showing the change in reflectance spectra of the 25 % CMYK ink patch from the Epson Pro 9000 ink set printed on the Somerset Velvet paper (3.3) after exposure to the fluorescent light tester with an UV filter.



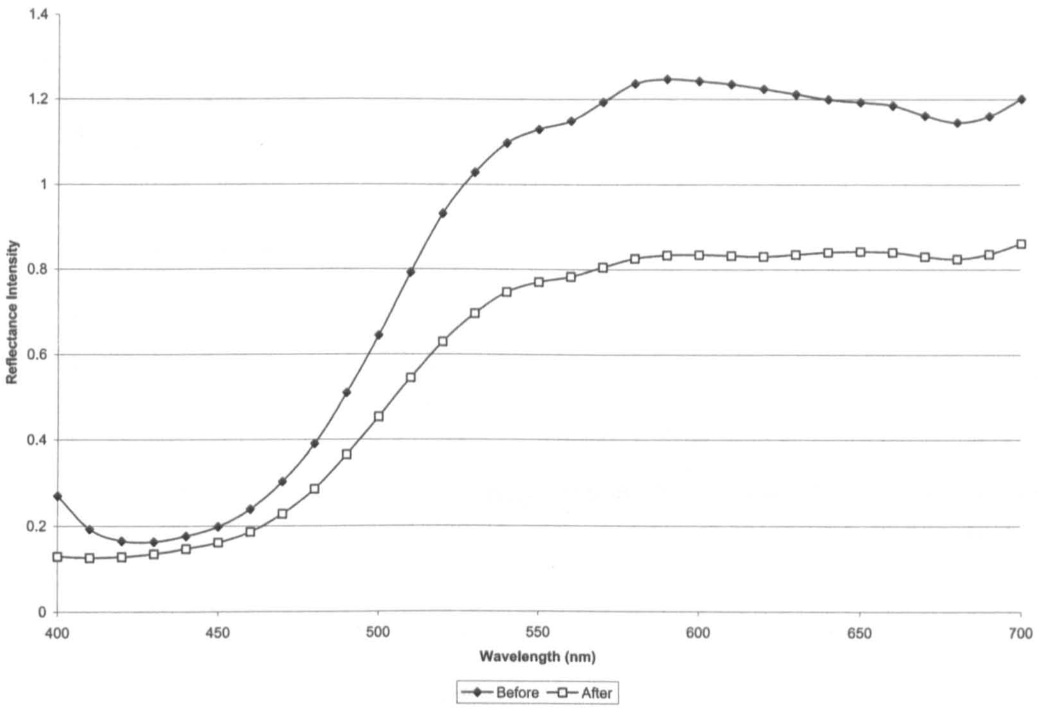
L.30 Plot showing the change in reflectance spectra of the 50 % CMYK ink patch from the Epson Pro 9000 ink set printed on ISVE paper (3.2) after exposure to the fluorescent light tester with an UV filter.



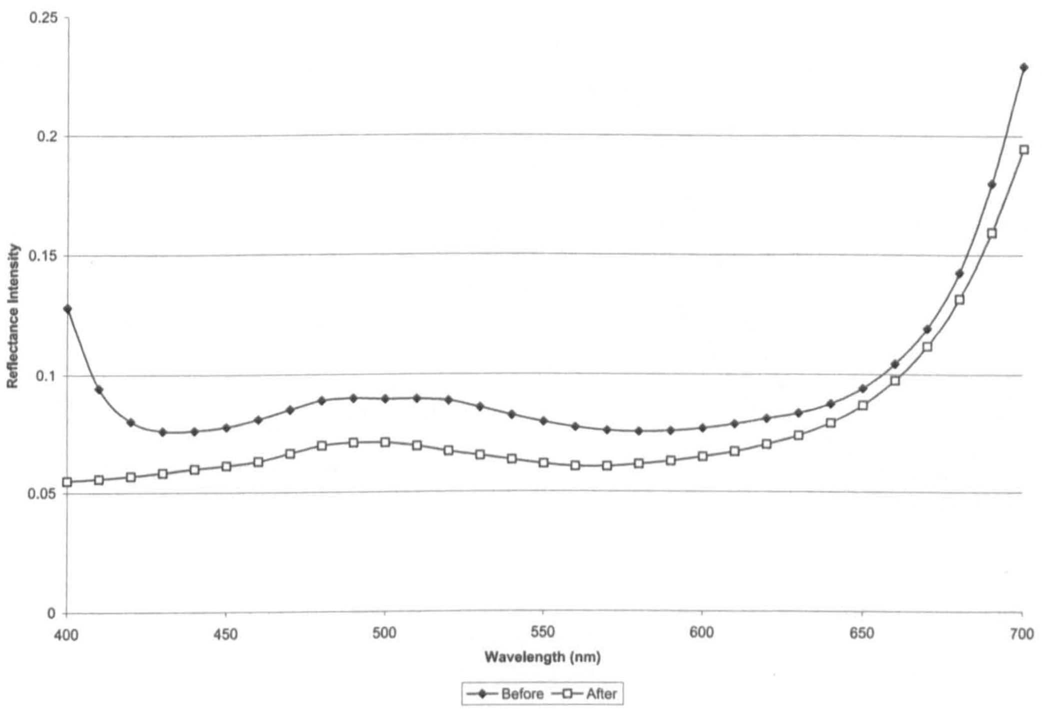
L.31 Plot showing the change in reflectance spectra of the cyan ink from the Epson Pro 9000 ink set printed on the Whatman watercolour paper (3.4) after exposure to the fluorescent light tester with an UV filter.



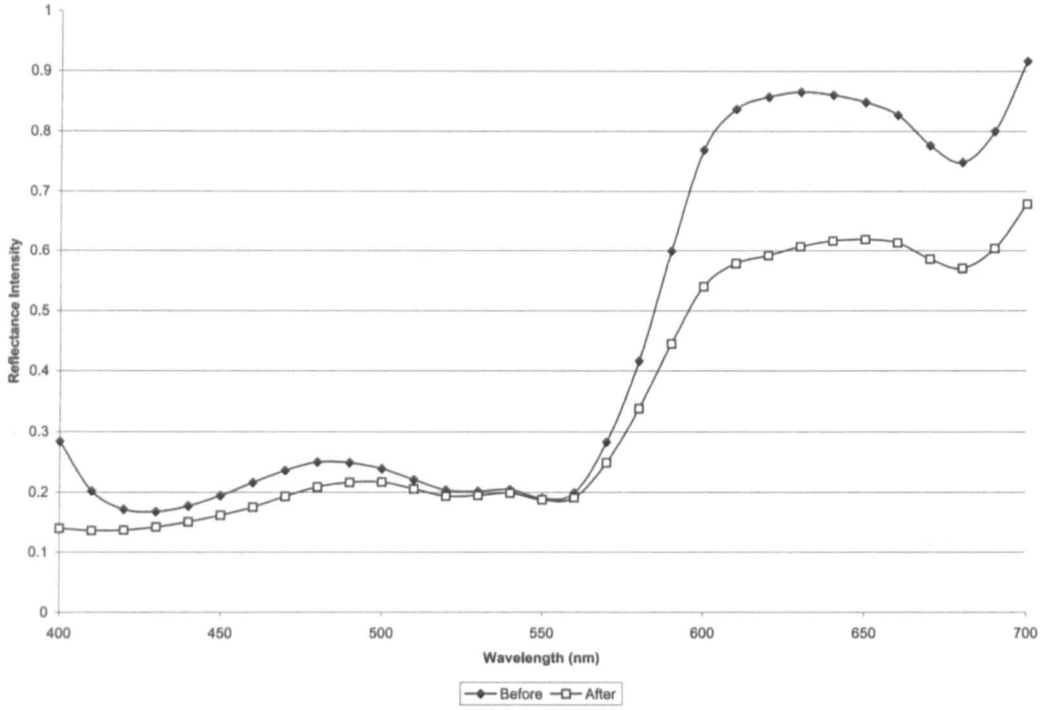
L.32 Plot showing the change in reflectance spectra of the magenta ink from the Epson Pro 9000 ink set printed on the Whatman watercolour paper (3.4) after exposure to the fluorescent light tester with an UV filter.



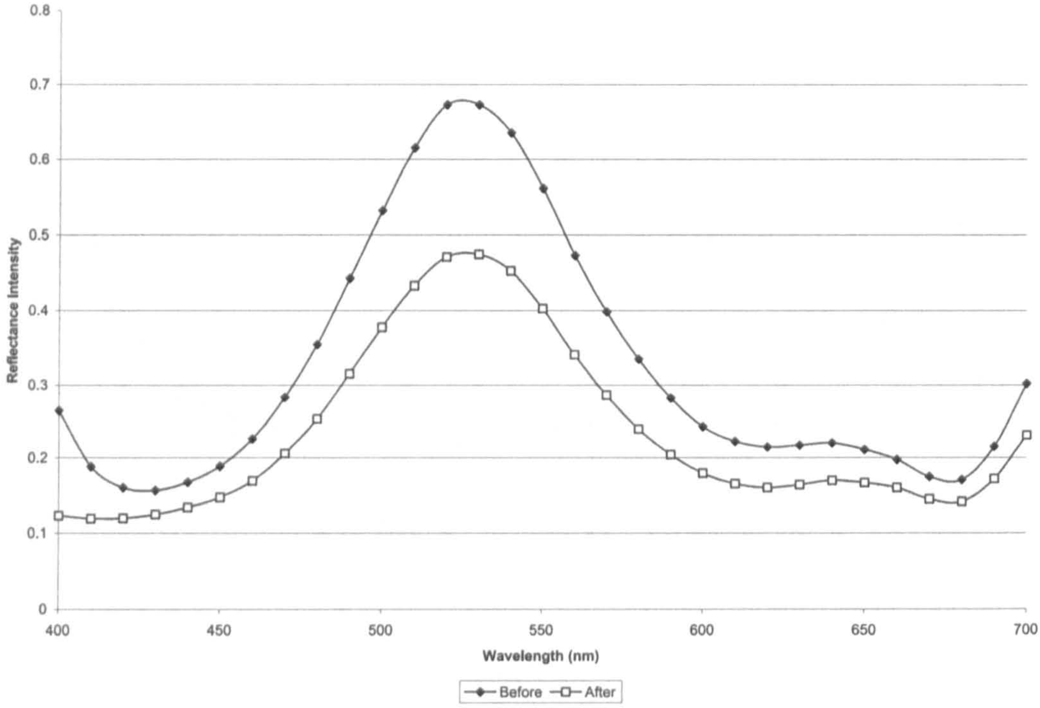
L.33 Plot showing the change in reflectance spectra of the yellow ink from the Epson Pro 9000 ink set printed on the Whatman watercolour paper (3.4) after exposure to the fluorescent light tester with an UV filter.



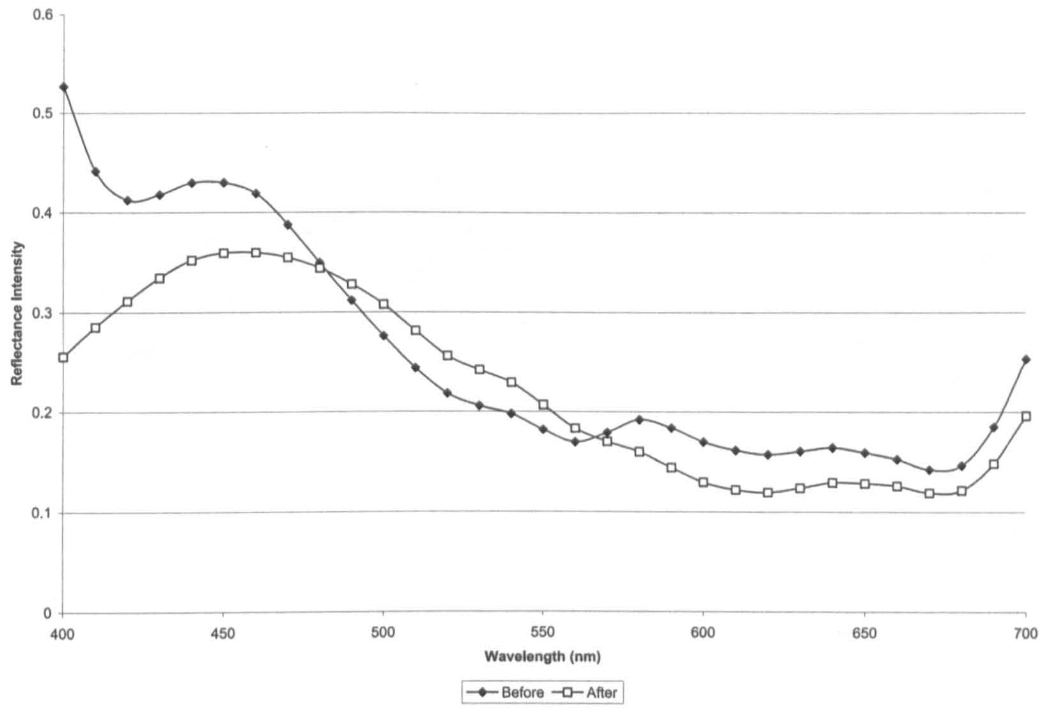
L.34 Plot showing the change in reflectance spectra of the black ink from the Epson Pro 9000 ink set printed on the Whatman watercolour paper (3.4) after exposure to the fluorescent light tester with an UV filter.



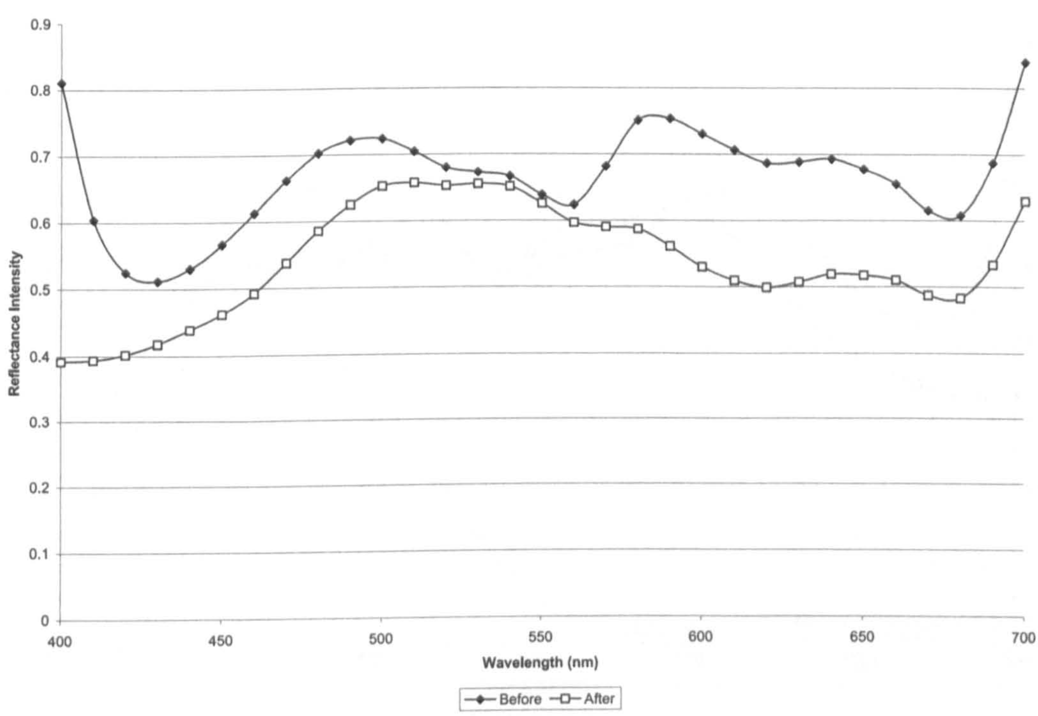
L.35 Plot showing the change in reflectance spectra of the red ink patch from the Epson Pro 9000 ink set printed on the Whatman watercolour paper (3.4) after exposure to the fluorescent light tester with an UV filter.



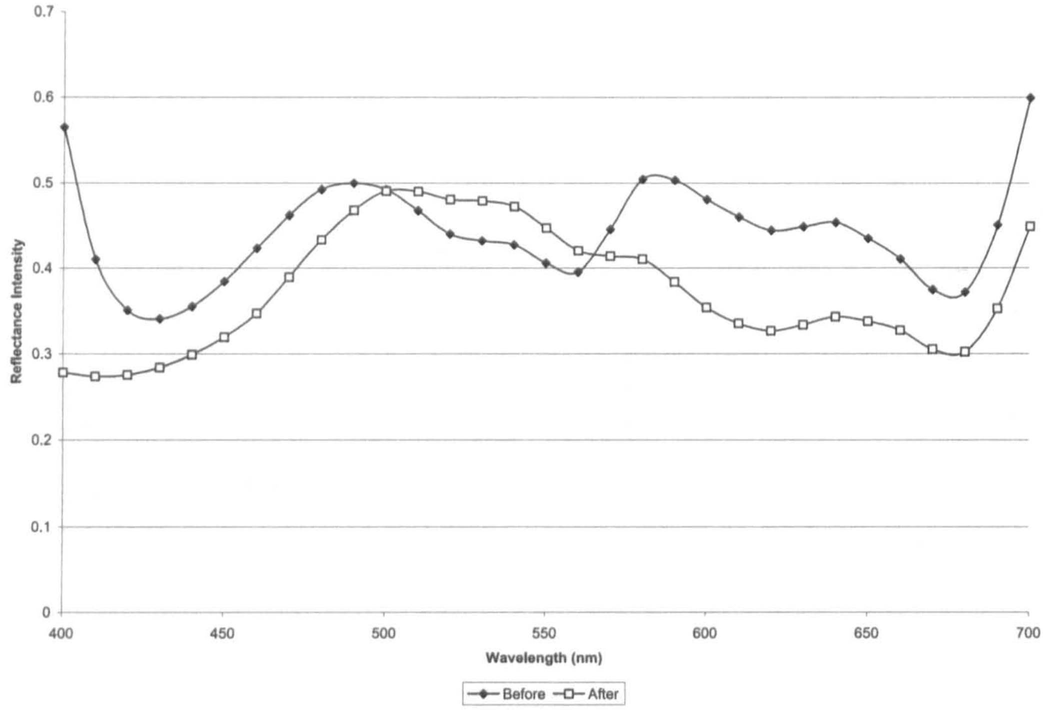
L.36 Plot showing the change in reflectance spectra of the green ink patch from the Epson Pro 9000 ink set printed on the Whatman watercolour paper (3.4) after exposure to the fluorescent light tester with an UV filter.



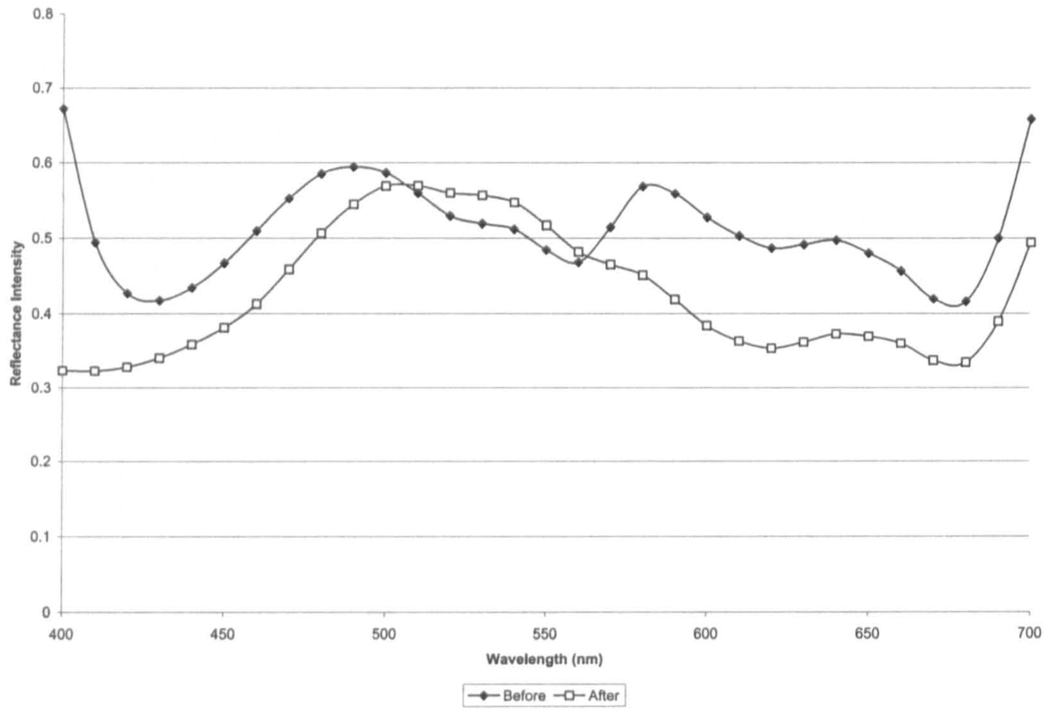
L.37 Plot showing the change in reflectance spectra of the blue ink patch from the Epson Pro 9000 ink set printed on the Whatman watercolour paper (3.4) after exposure to the fluorescent light tester with an UV filter.



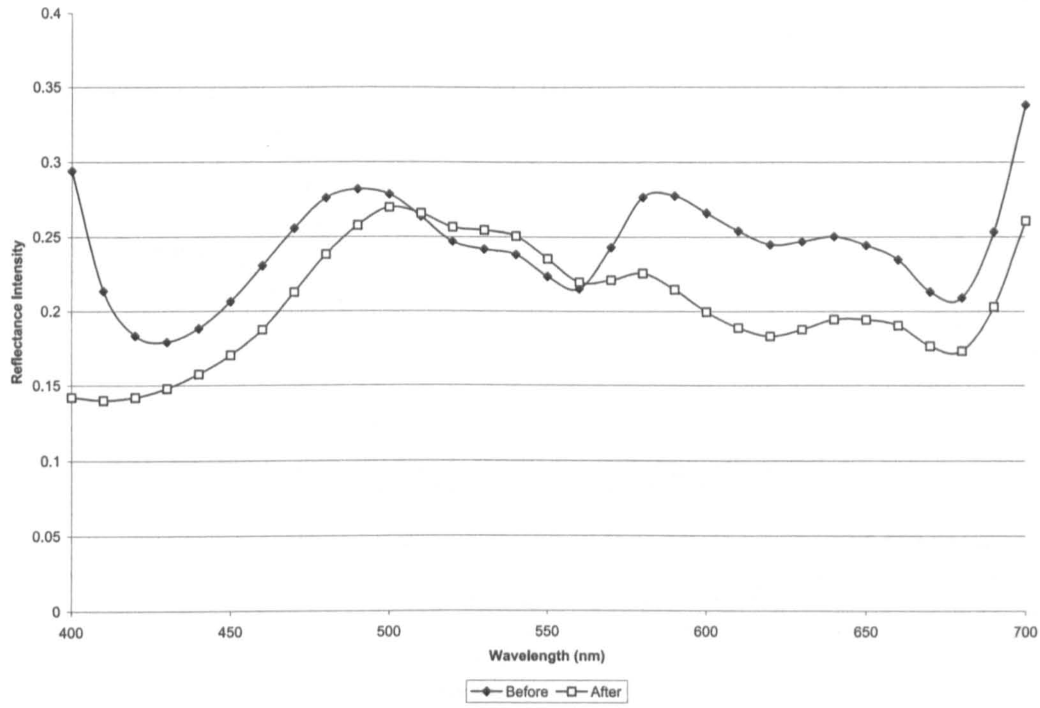
L.38 Plot showing the change in reflectance spectra of the 25 % CMY ink patch from the Epson Pro 9000 ink set printed on the Whatman watercolour paper (3.4) after exposure to the fluorescent light tester with an UV filter.



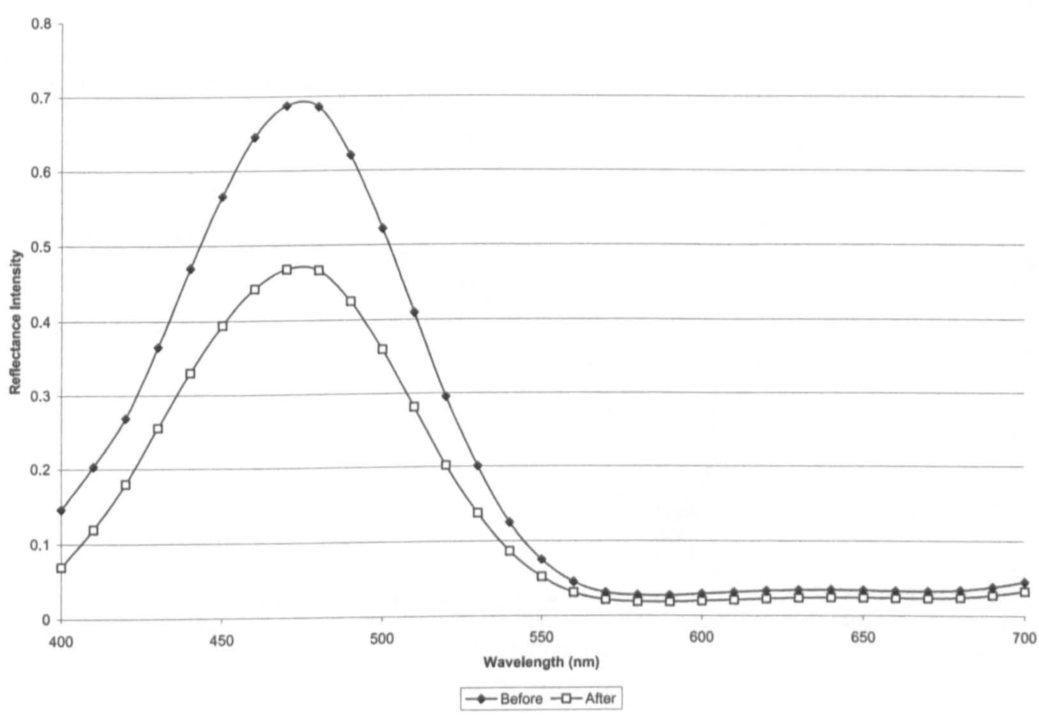
L.39 Plot showing the change in reflectance spectra of the 50 % CMY ink patch from the Epson Pro 9000 ink set printed on the Whatman watercolour paper (3.4) after exposure to the fluorescent light tester with an UV filter.



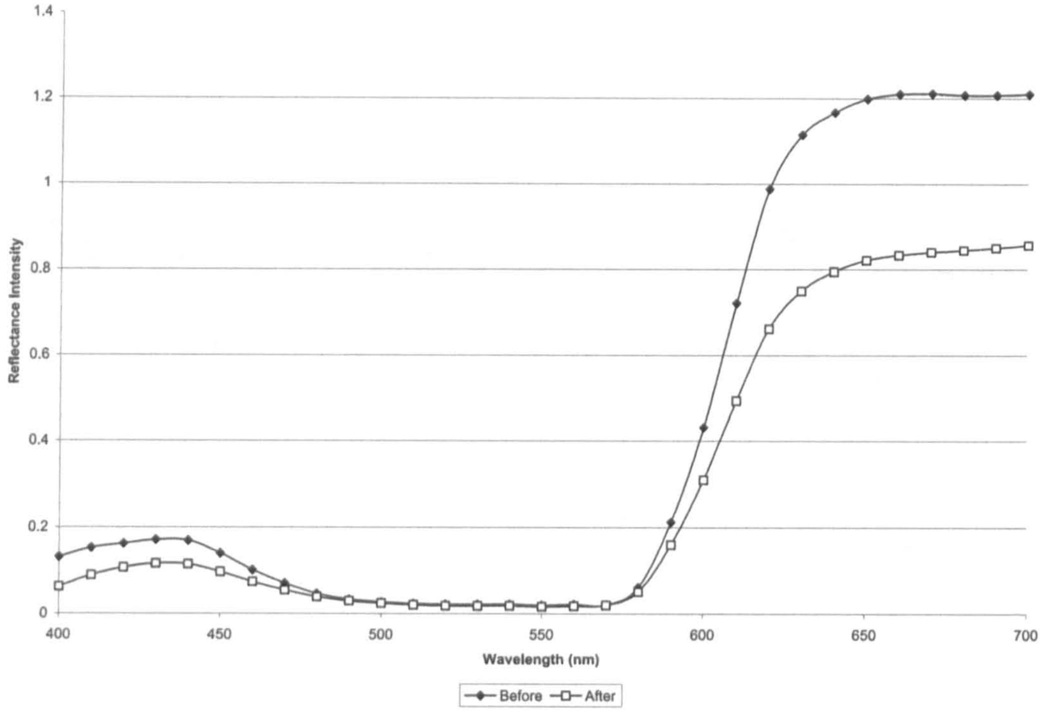
L.40 Plot showing the change in reflectance spectra of the 25 % CMYK ink patch from the Epson Pro 9000 ink set printed on the Whatman watercolour paper (3.4) after exposure to the fluorescent light tester with an UV filter.



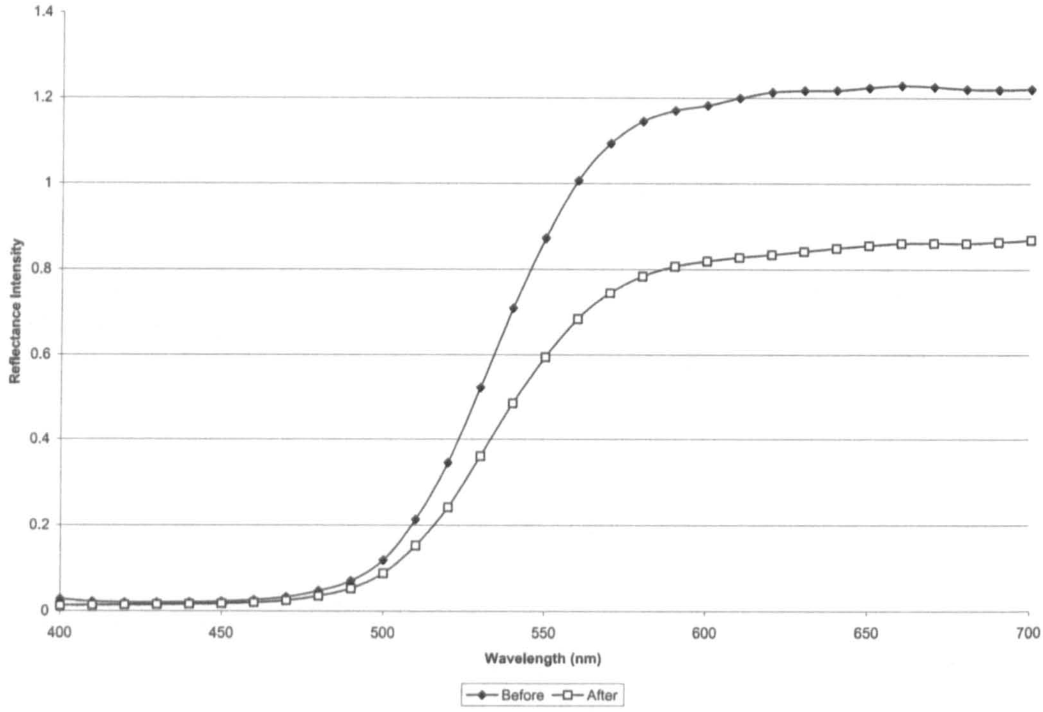
L.41 Plot showing the change in reflectance spectra of the 50 % CMYK ink patch from the Epson Pro 9000 ink set printed on the Whatman watercolour paper (3.4) after exposure to the fluorescent light tester with an UV filter.



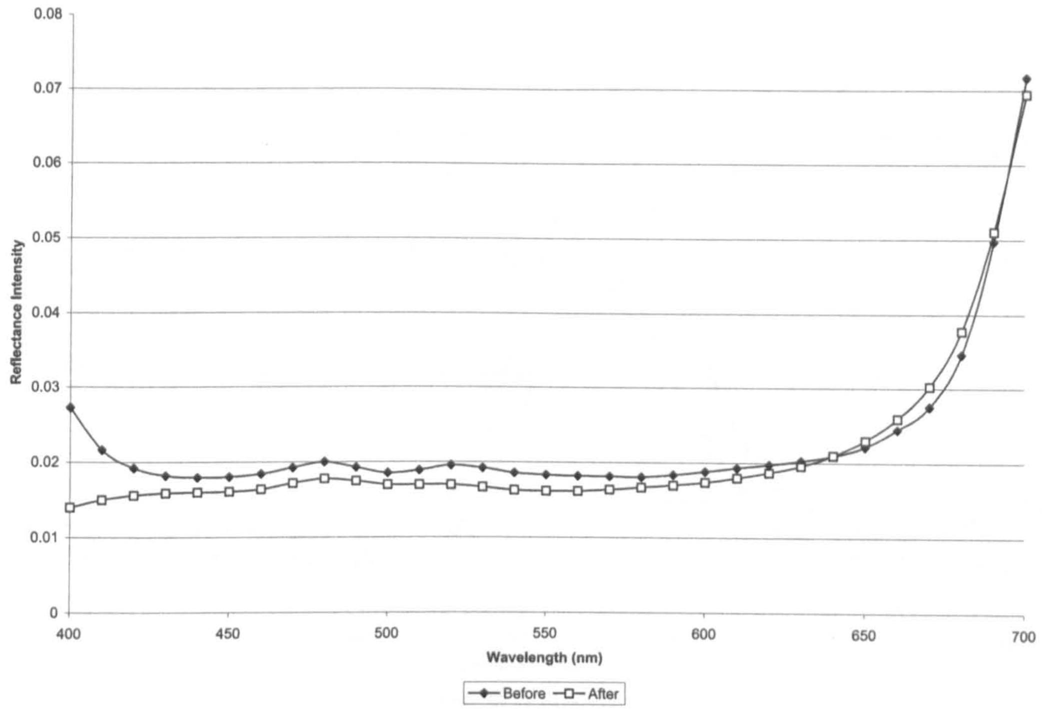
L.42 Plot showing the change in reflectance spectra of the cyan ink from the Epson Pro 9000 ink set printed on the Epson Presentation Matt paper (3.5) after exposure to the fluorescent light tester with an UV filter.



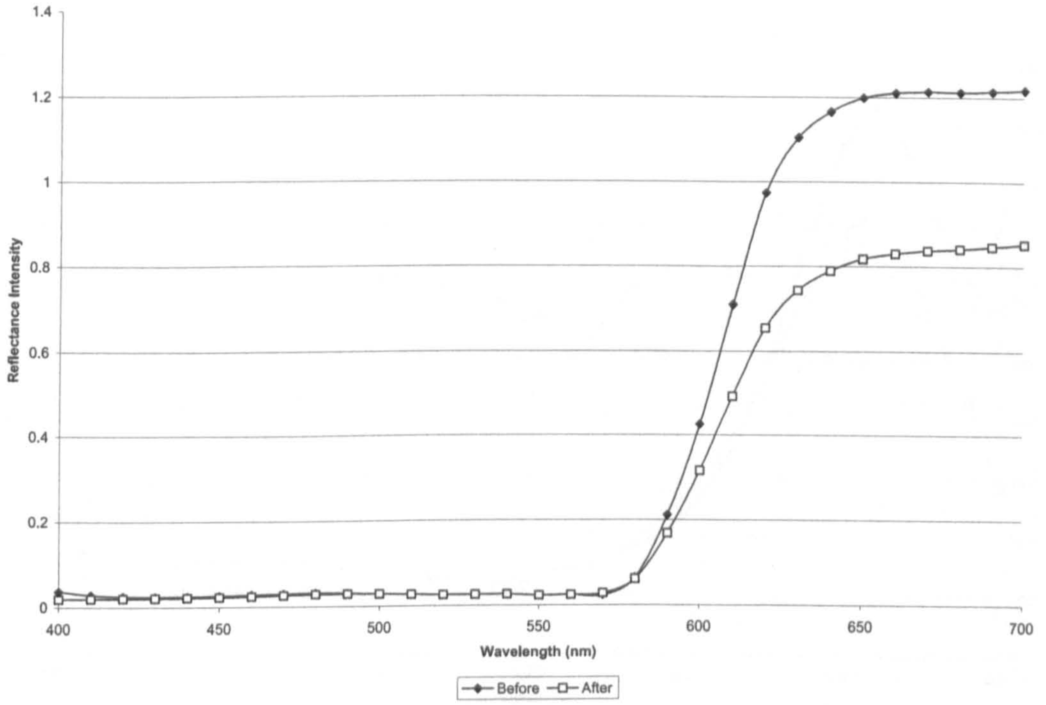
L.43 Plot showing the change in reflectance spectra of the magenta ink from the Epson Pro 9000 ink set printed on the Epson Presentation Matt paper (3.5) after exposure to the fluorescent light tester with an UV filter.



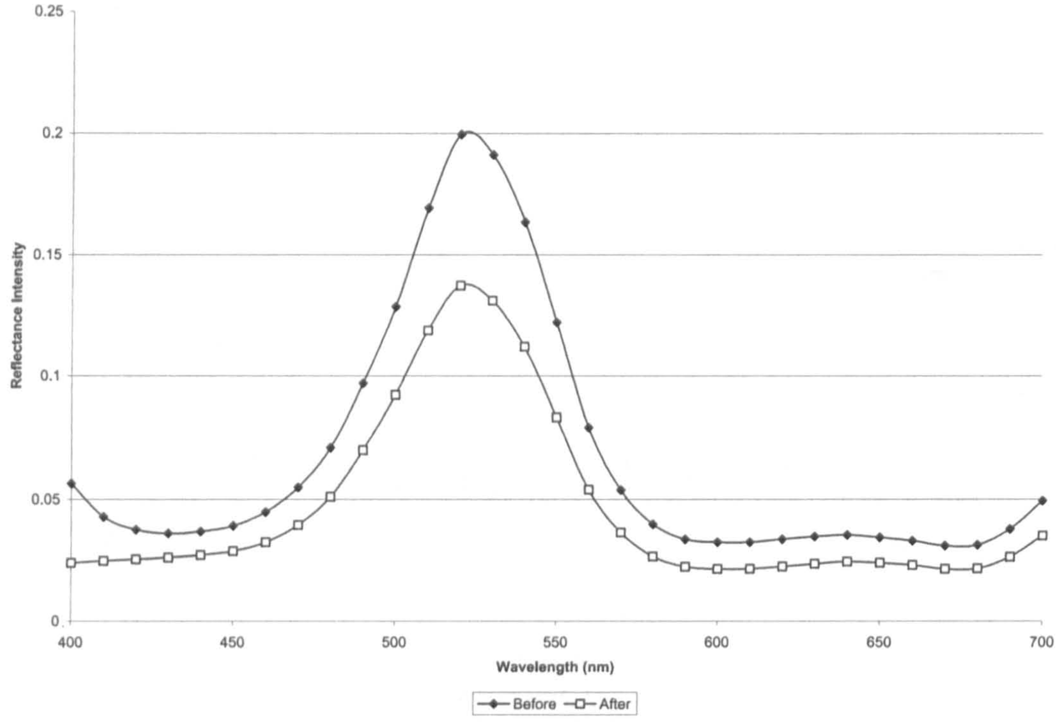
L.44 Plot showing the change in reflectance spectra of the yellow ink from the Epson Pro 9000 ink set printed on the Epson Presentation Matt paper (3.5) after exposure to the fluorescent light tester with an UV filter.



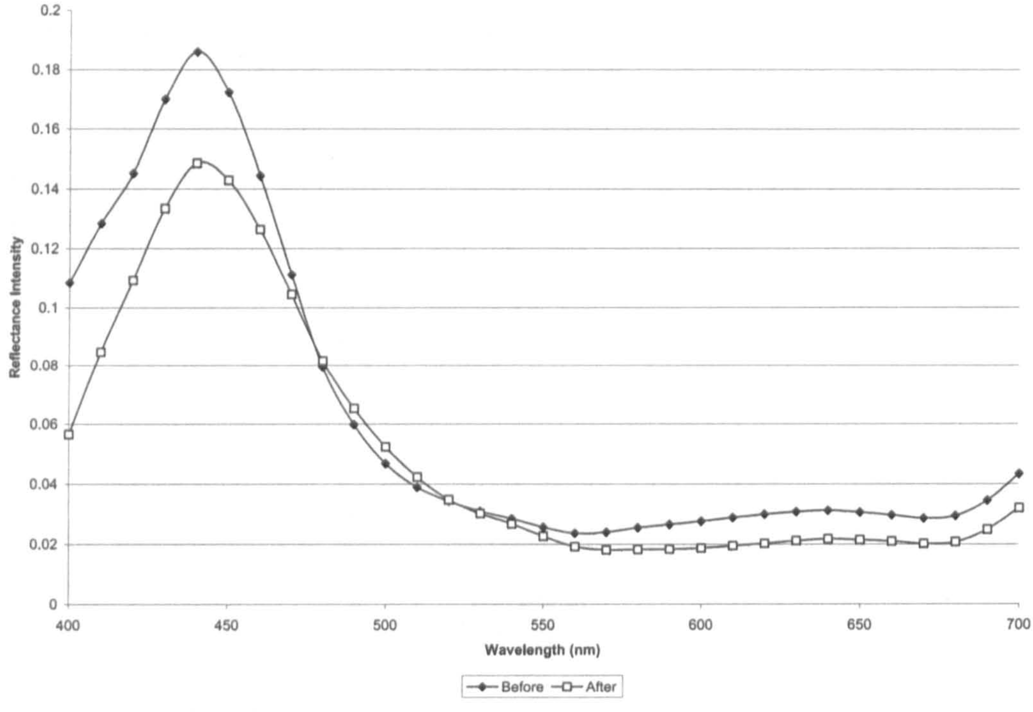
L.45 Plot showing the change in reflectance spectra of the black ink from the Epson Pro 9000 ink set printed on the Epson Presentation Matt paper (3.5) after exposure to the fluorescent light tester with an UV filter.



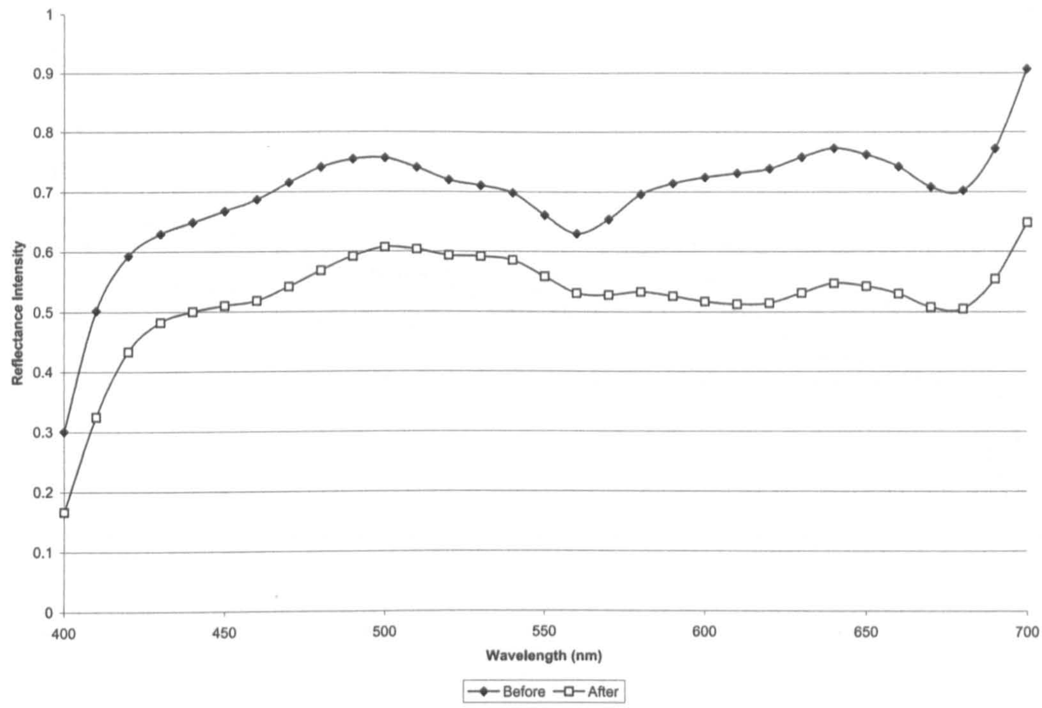
L.46 Plot showing the change in reflectance spectra of the red ink patch from the Epson Pro 9000 ink set printed on the Epson Presentation Matt paper (3.5) after exposure to the fluorescent light tester with an UV filter.



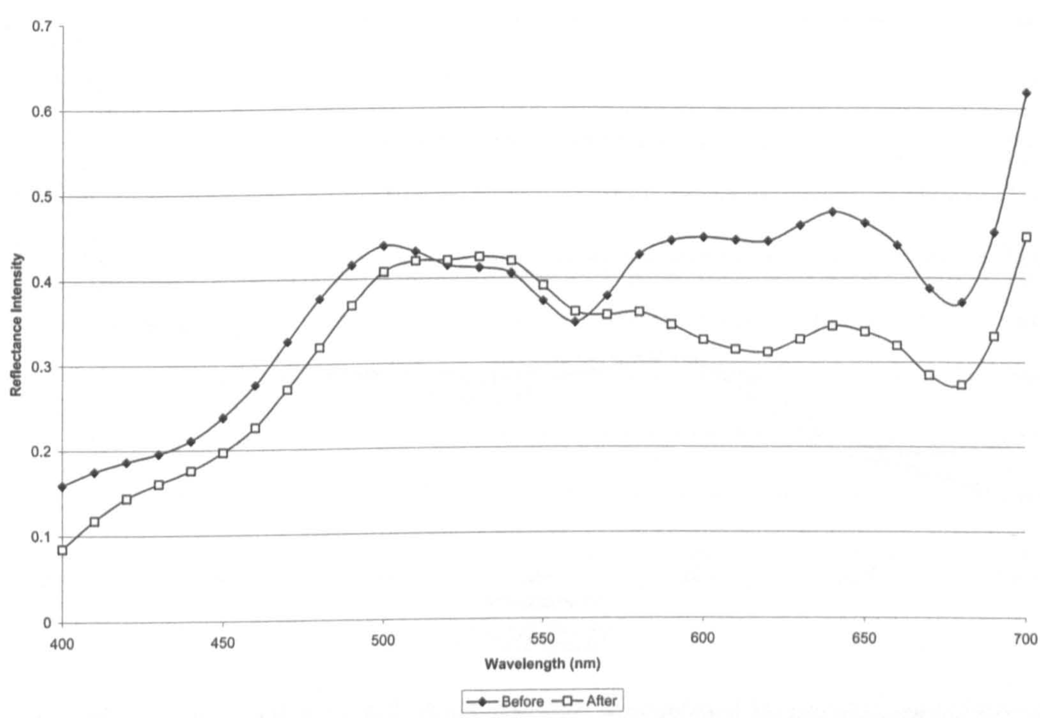
L.47 Plot showing the change in reflectance spectra of the green ink patch from the Epson Pro 9000 ink set printed on the Epson Presentation Matt paper (3.5) after exposure to the fluorescent light tester with an UV filter.



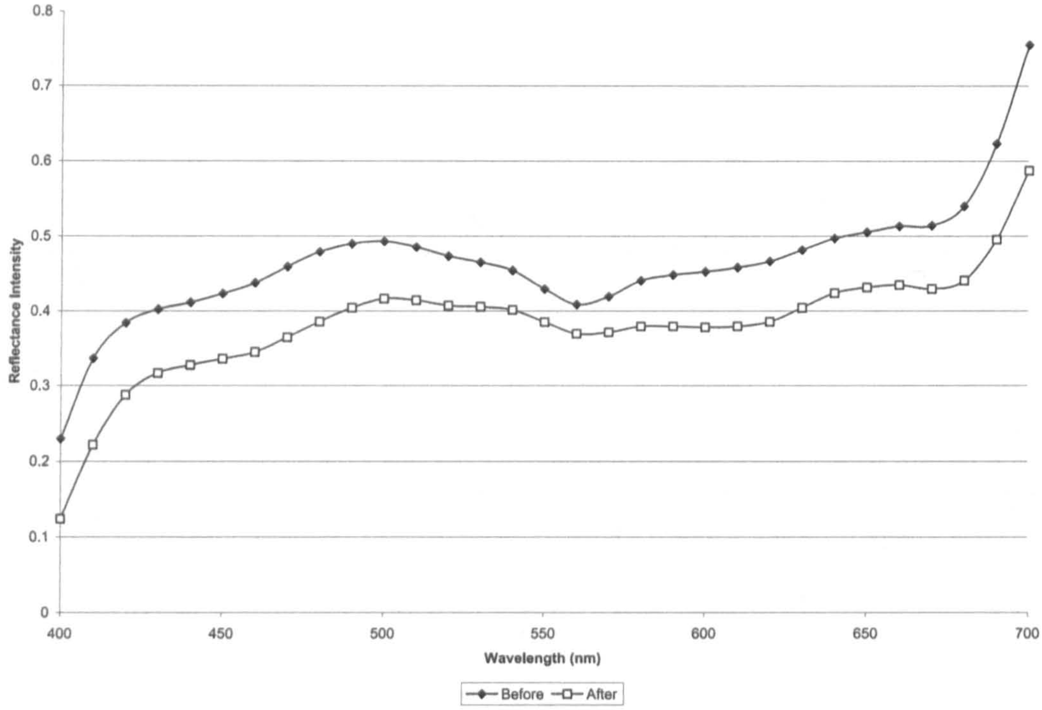
L.48 Plot showing the change in reflectance spectra of the blue ink patch from the Epson Pro 9000 ink set printed on the Epson Presentation Matt paper (3.5) after exposure to the fluorescent light tester with an UV filter.



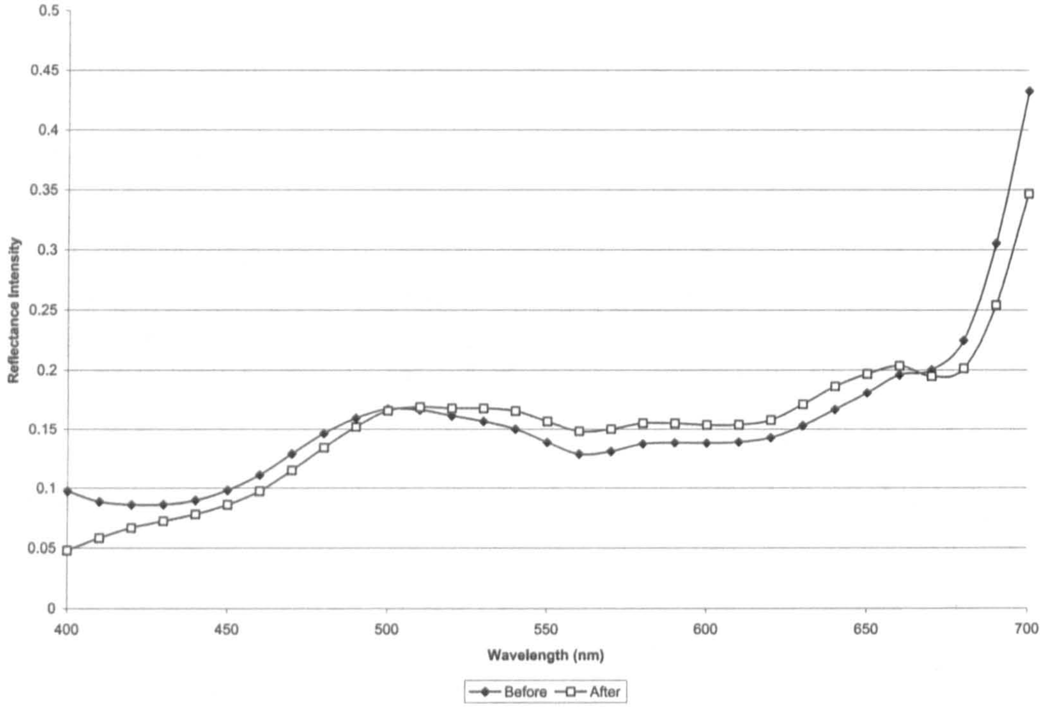
L.49 Plot showing the change in reflectance spectra of the 25 % CMY ink patch from the Epson Pro 9000 ink set printed on the Epson Presentation Matt paper (3.5) after exposure to the fluorescent light tester with an UV filter.



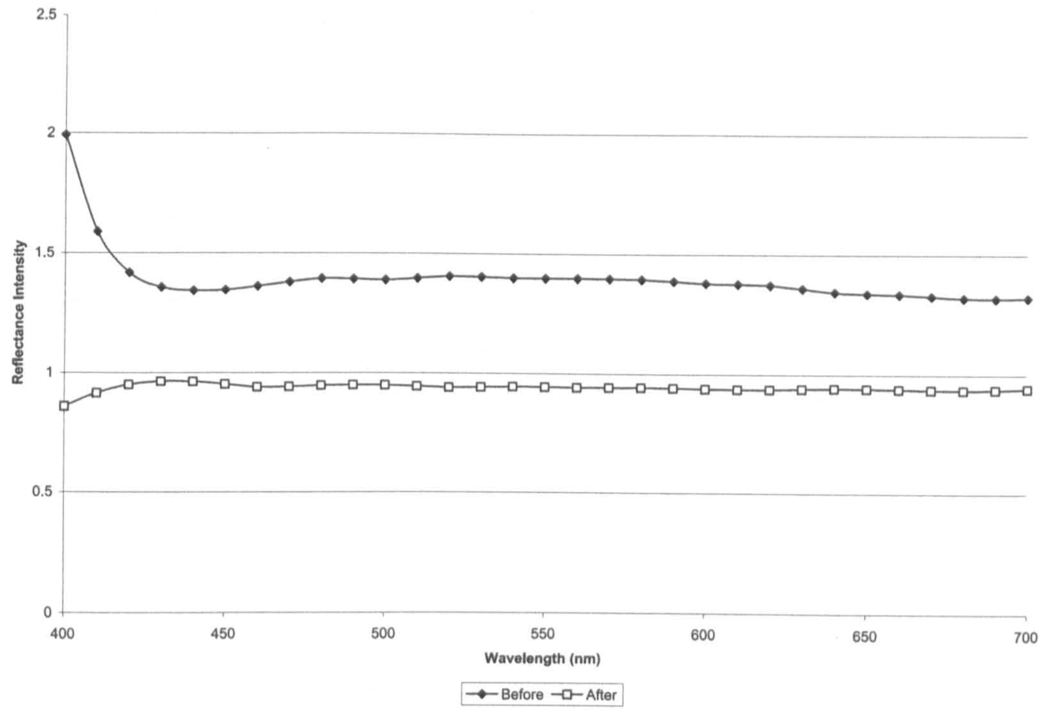
L.50 Plot showing the change in reflectance spectra of the 50 % CMY ink patch from the Epson Pro 9000 ink set printed on the Epson Presentation Matt paper (3.5) after exposure to the fluorescent light tester with an UV filter.



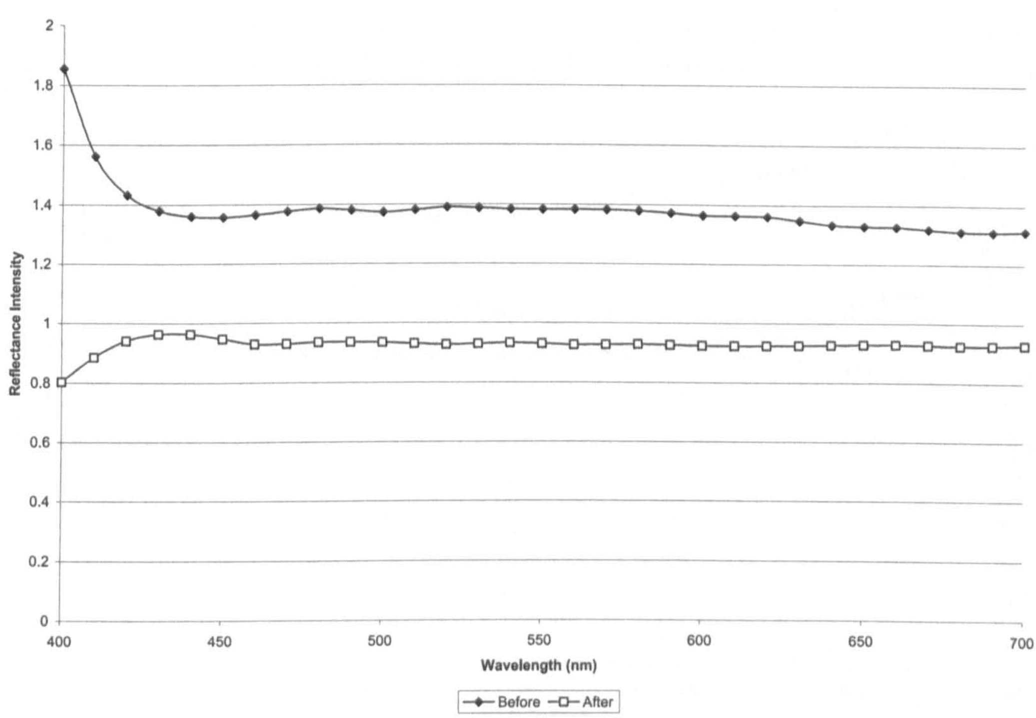
L.51 Plot showing the change in reflectance spectra of the 25 % CMYK ink patch from the Epson Pro 9000 ink set printed on the Epson Presentation Matt paper (3.5) after exposure to the fluorescent light tester with an UV filter.



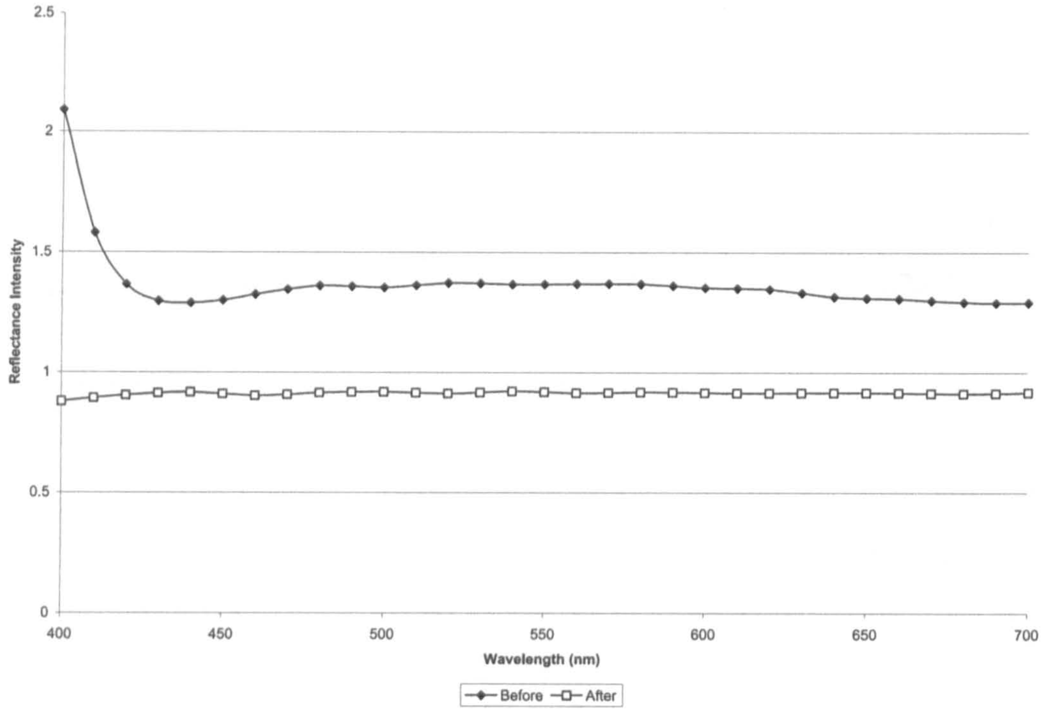
L.52 Plot showing the change in reflectance spectra of the 50 % CMYK ink patch from the Epson Pro 9000 ink set printed on the Epson Presentation Matt paper (3.5) after exposure to the fluorescent light tester with an UV filter.



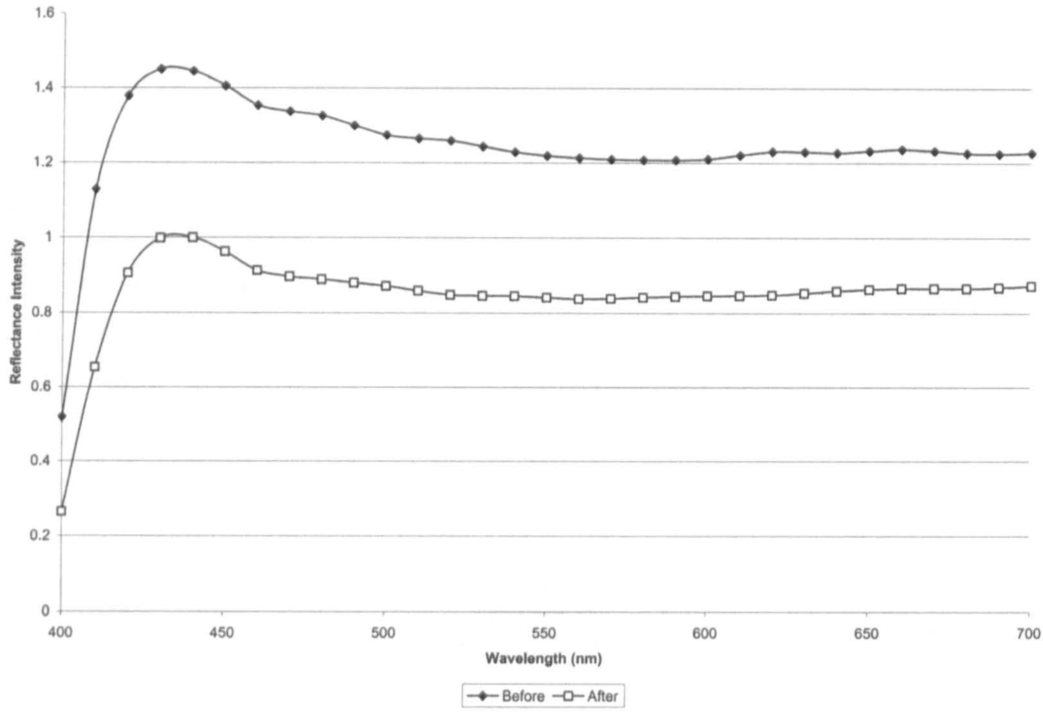
L.53 Plot showing the change in reflectance spectra of the ISVE paper after exposure to the fluorescent light tester with an UV filter.



L.54 Plot showing the change in reflectance spectra of the Somerset Velvet paper after exposure to the fluorescent light tester with an UV filter.

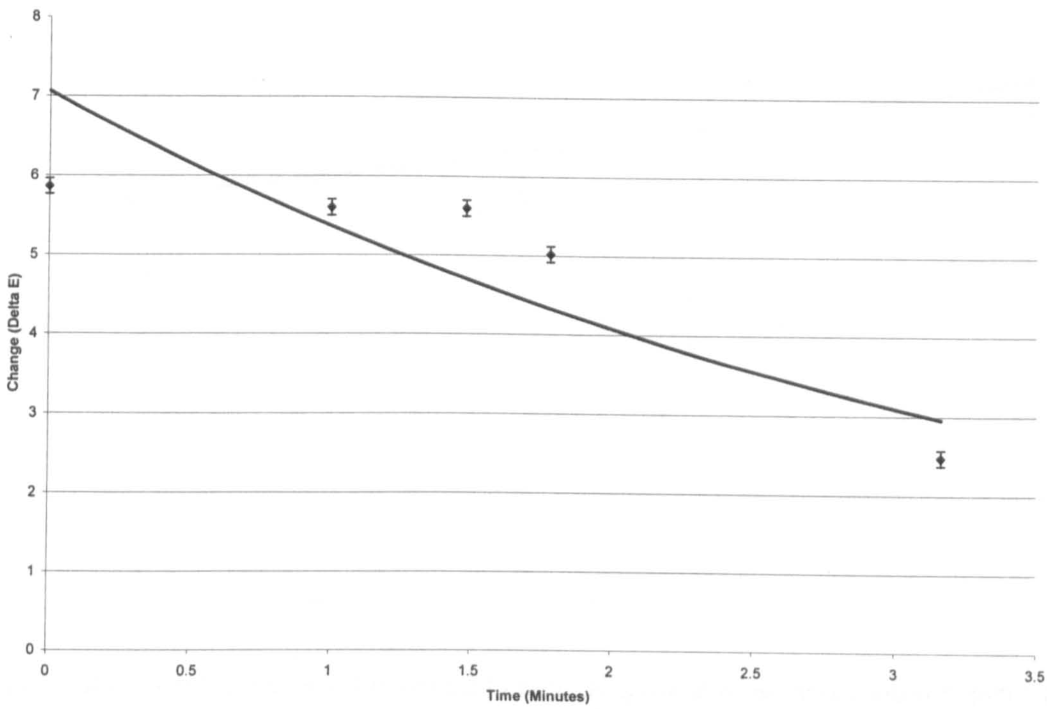


L.55 Plot showing the change in reflectance spectra of the Whatman watercolour paper after exposure to the fluorescent light tester with an UV filter.

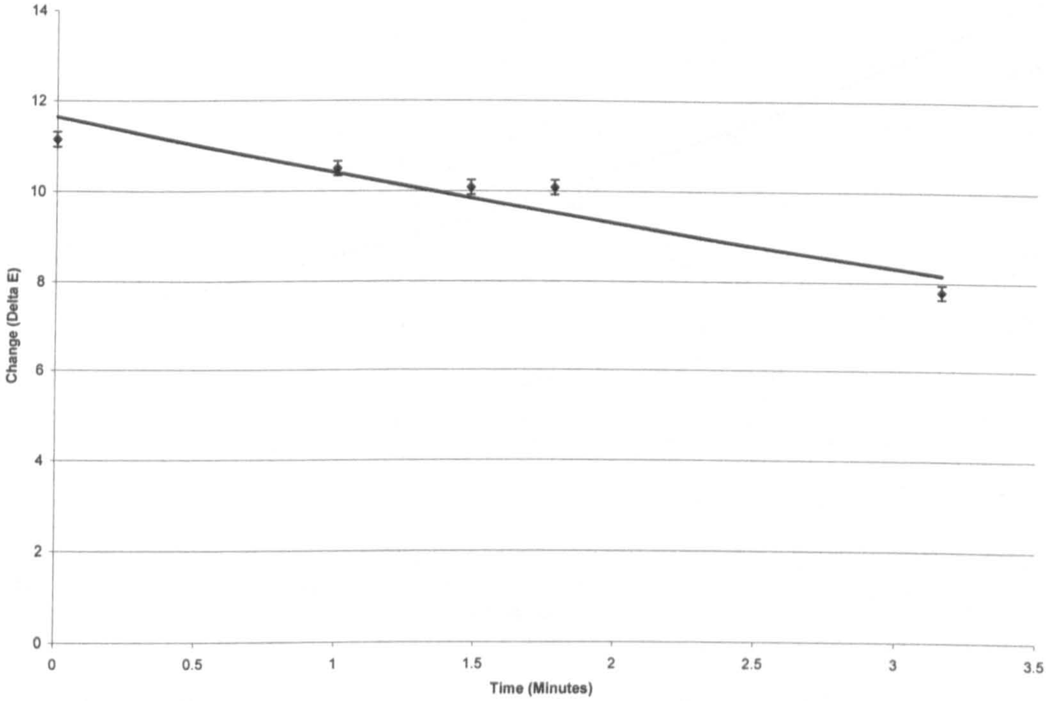


L.56 Plot showing the change in reflectance spectra of the Epson Presentation Matt paper after exposure to the fluorescent light tester with an UV filter.

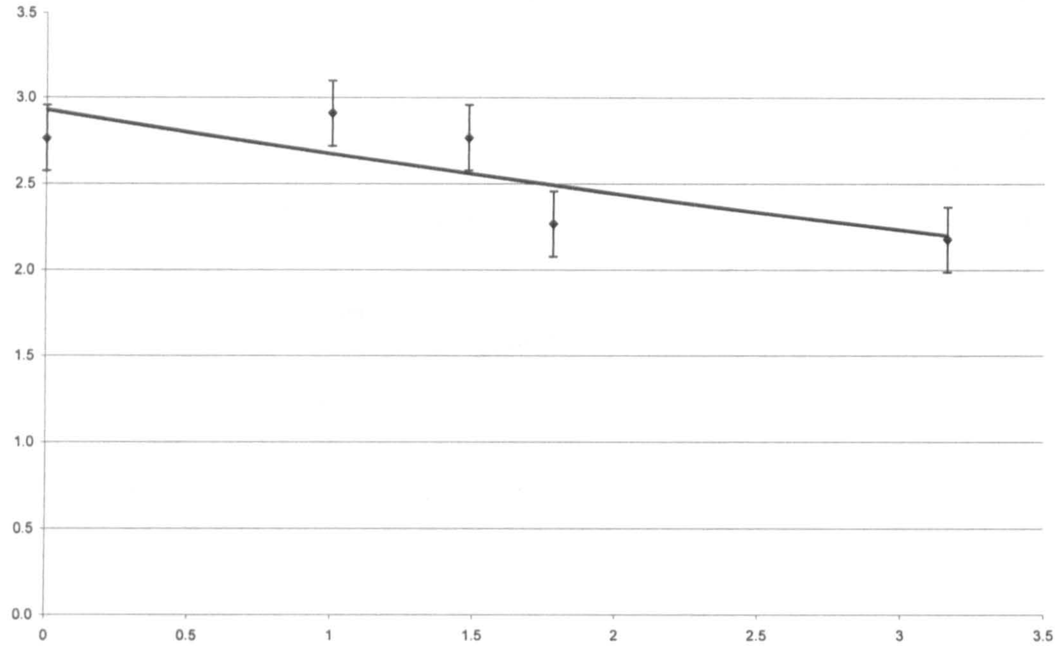
APPENDIX M - Photochromism graphs



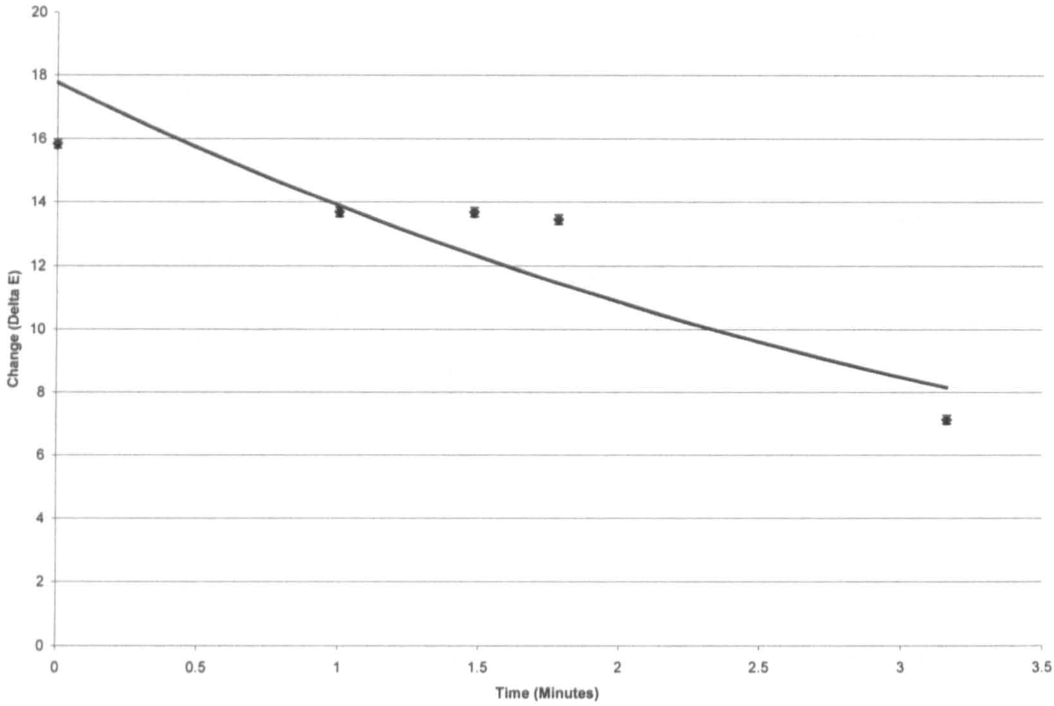
M.1 Plot showing the change in ΔEab against time of the yellow ink from the Epson Pro 9000 ink set printed on the Epson Photo Glossy paper (3.1), after the sample was removed from the Microscal Light Fastness Tester (including standard deviation results).



M.2 Plot showing the change in ΔEab against time of the cyan ink from the Epson Pro 9000 ink set printed on the Epson Presentation Matt paper (3.5), after the sample was removed from the Microscal Light Fastness Tester (including standard deviation results).

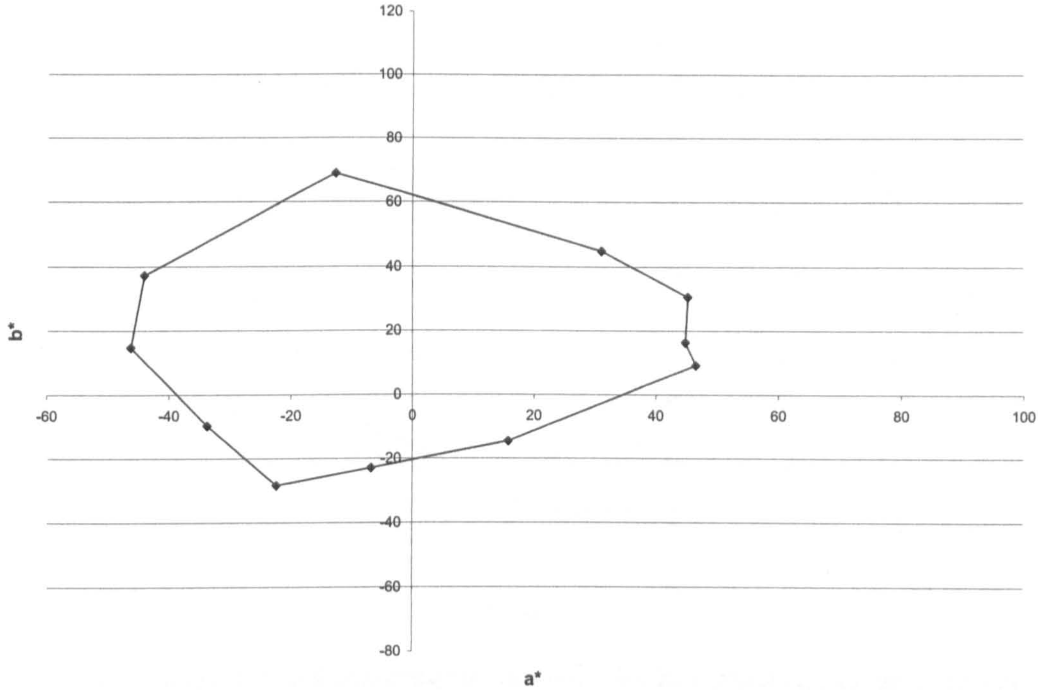


M.3 Plot showing the change in ΔEab against time of the yellow ink from the Epson Photo Stylus ink set printed on the Epson Photo Stylus Glossy paper (3.6), after the sample was removed from the Microscal Light Fastness Tester (including standard deviation results).

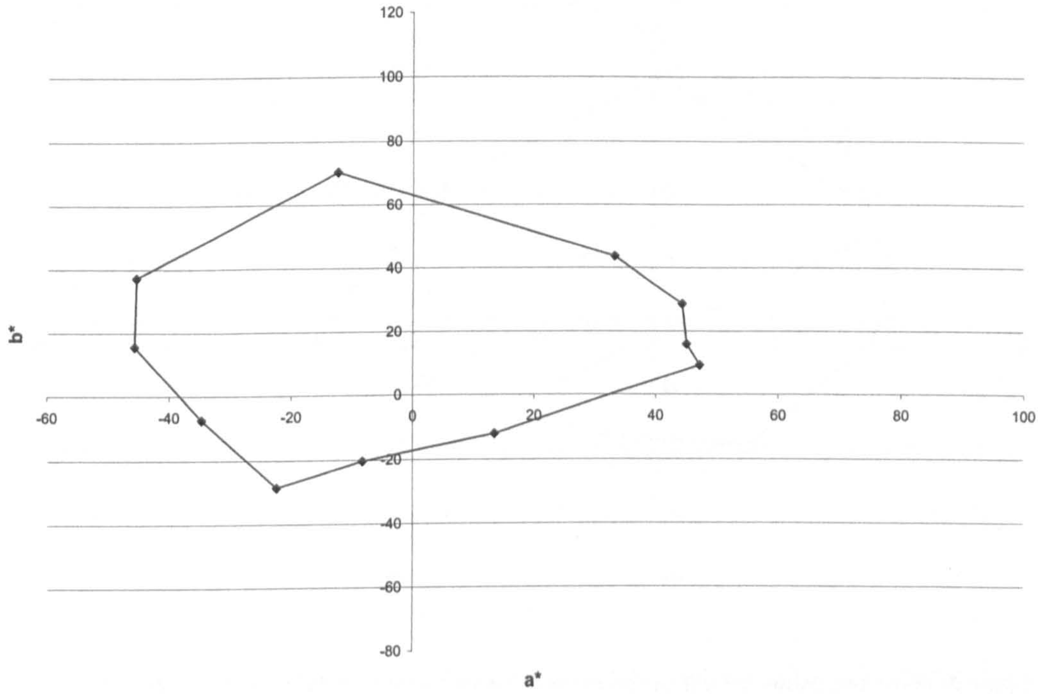


M.4 Plot showing the change in ΔEab against time of the yellow ink from the HP 3500 ink set printed on the HP Heavy Weight Coated paper (4.1), after the sample was removed from the Microscal Light Fastness Tester (including standard deviation results).

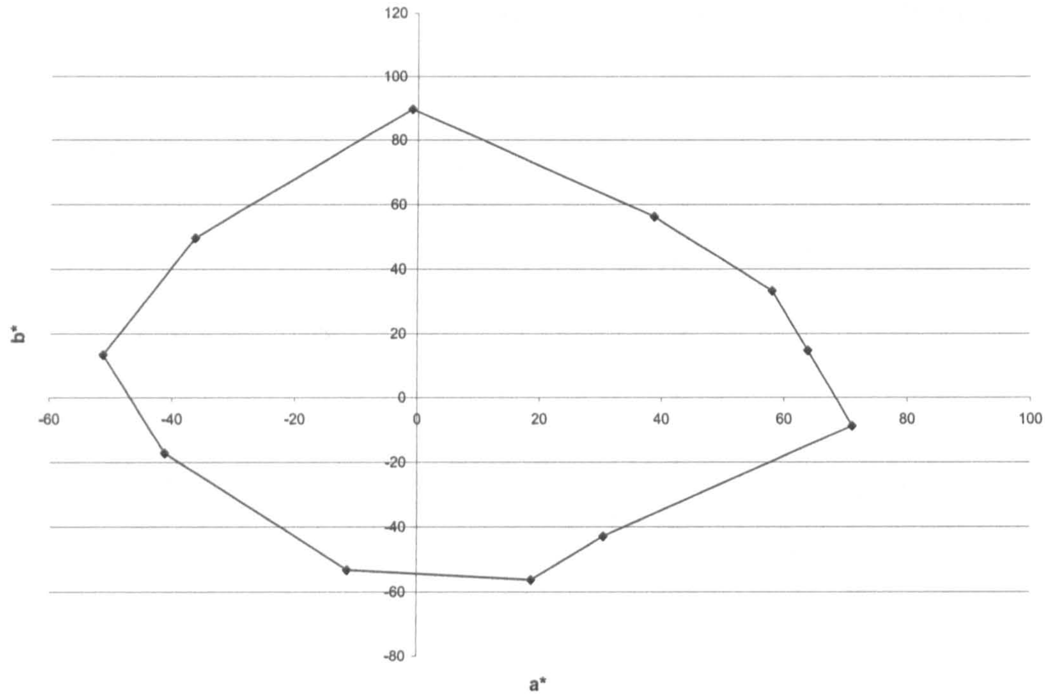
APPENDIX N - Colour gamut graphs



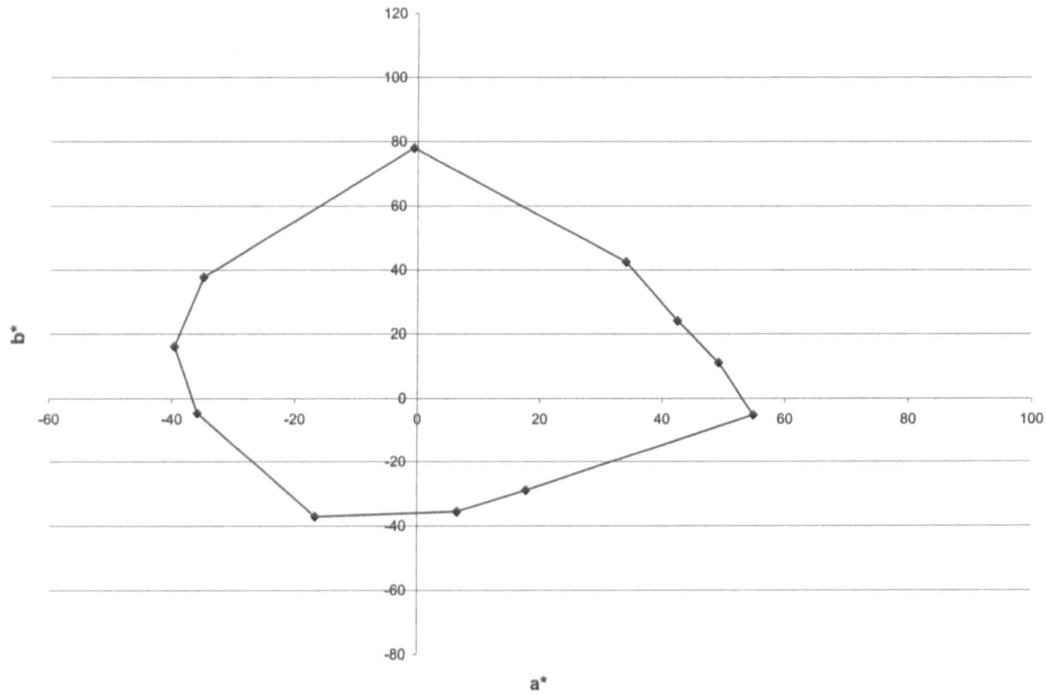
N.1 Plot showing the colour gamut of the Iris Morgan FA ink set printed on Somerset Velvet paper (1.1).



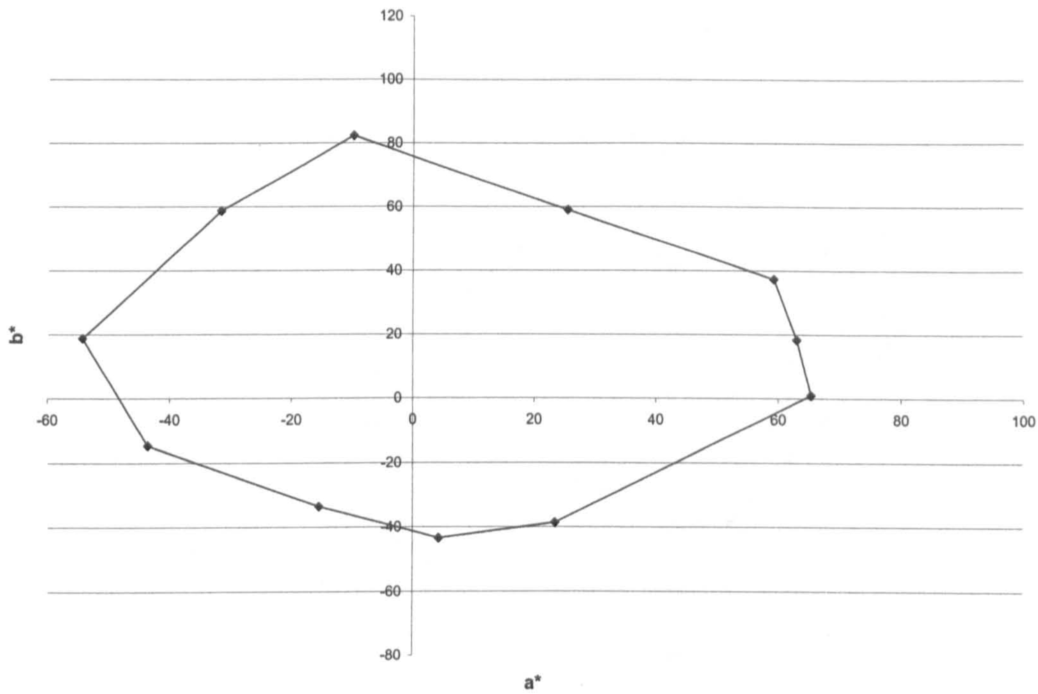
N.2 Plot showing the colour gamut of the Iris Morgan FA ink set printed on Whatman paper (1.2).



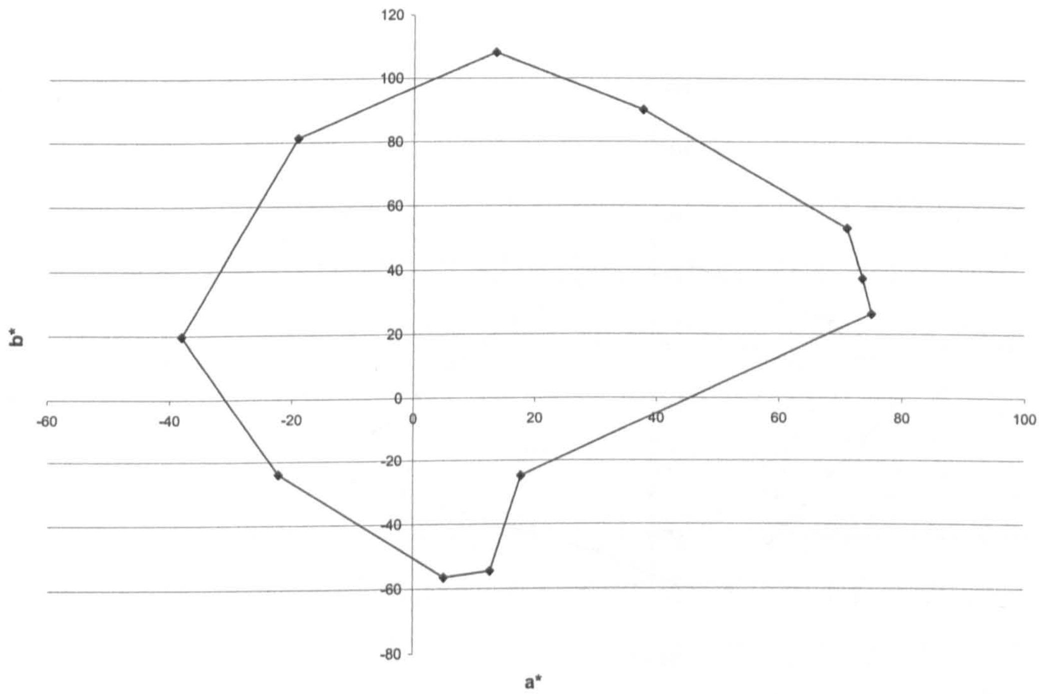
N.3 Plot showing the colour gamut of the Fotonic ink set printed on Lyson Rough Fine Art paper (2.2).



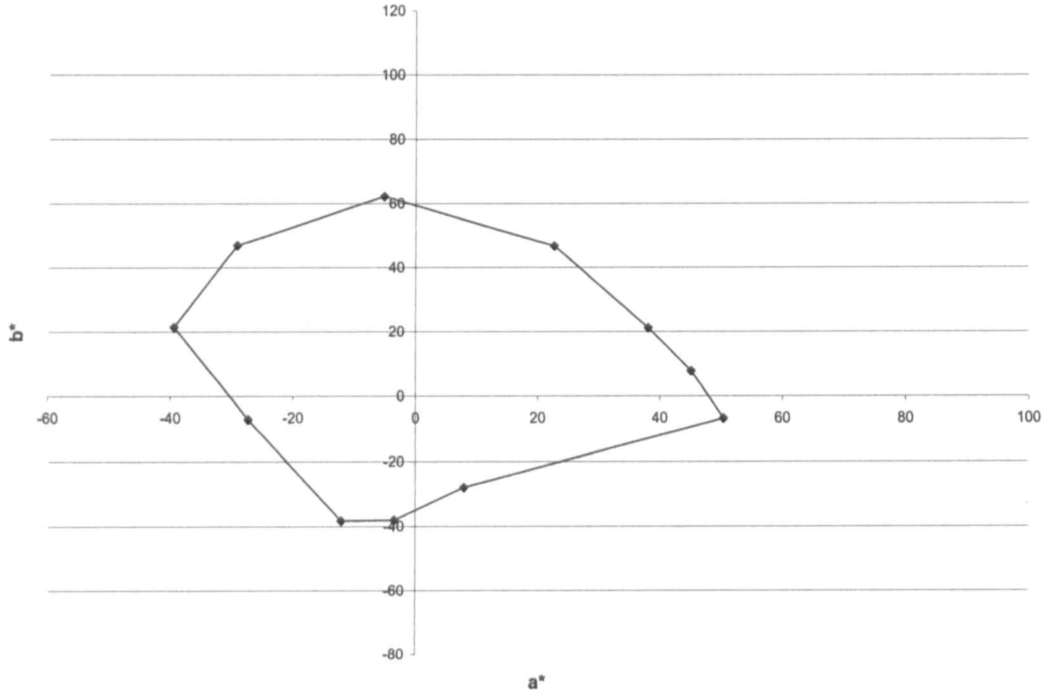
N.4 Plot showing the colour gamut of the Fotonic ink printed on Whatman paper (2.4).



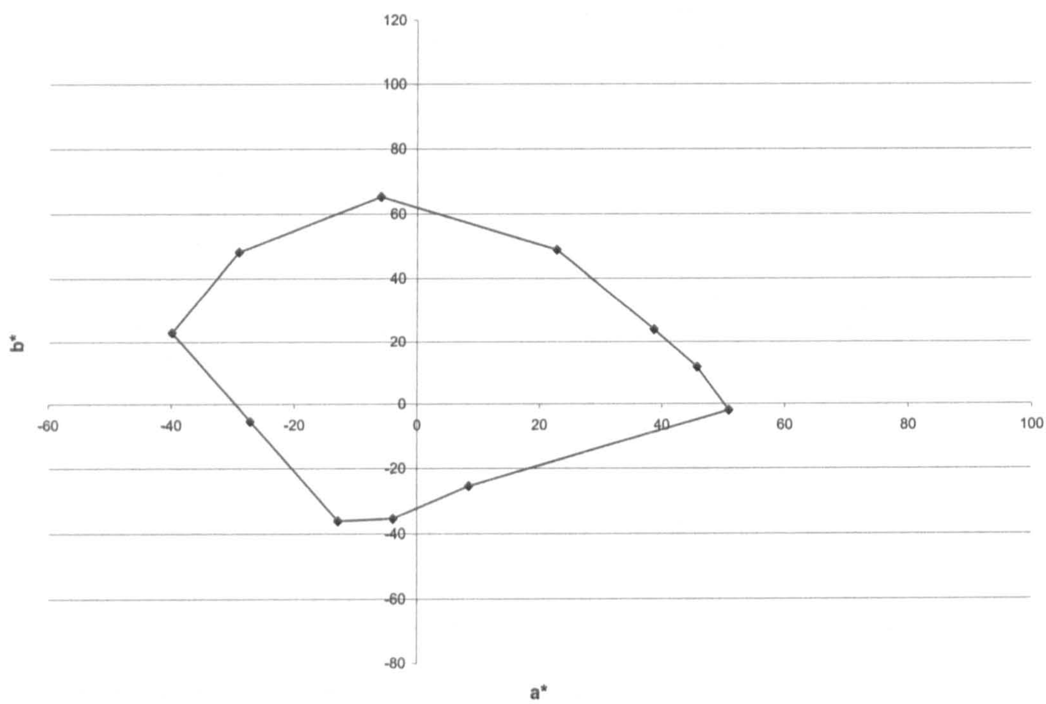
N.5 Plot showing the colour gamut of the Epson Pro 9000 ink set printed on Epson Photo Glossy paper (3.1).



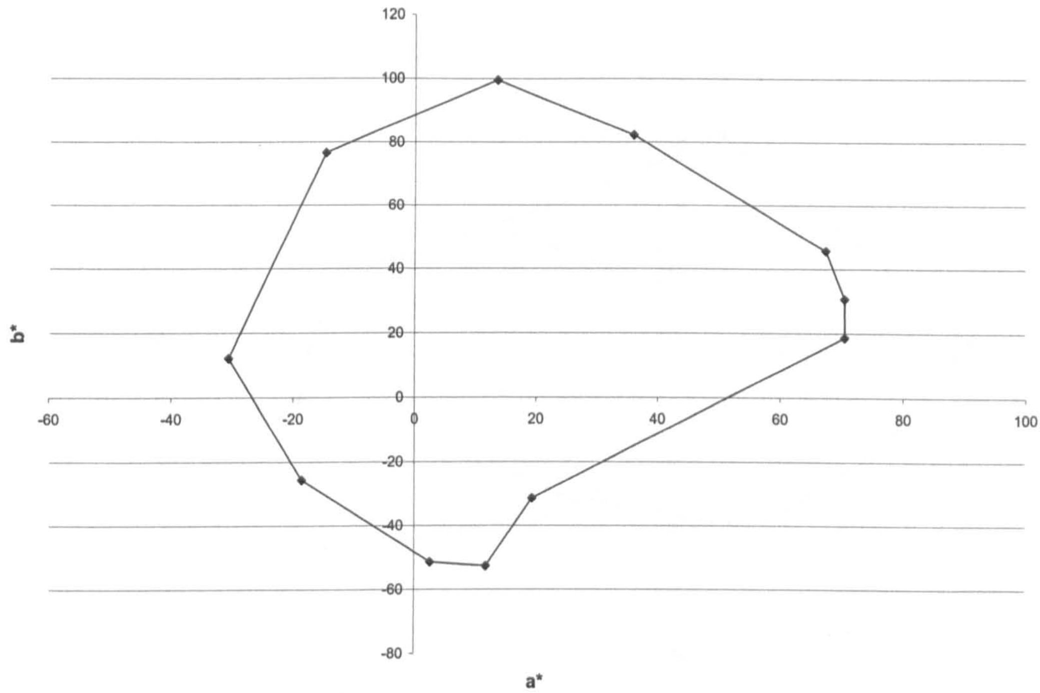
N.6 Plot showing the colour gamut of the Epson Pro 9000 ink set printed on ISVE paper (3.2).



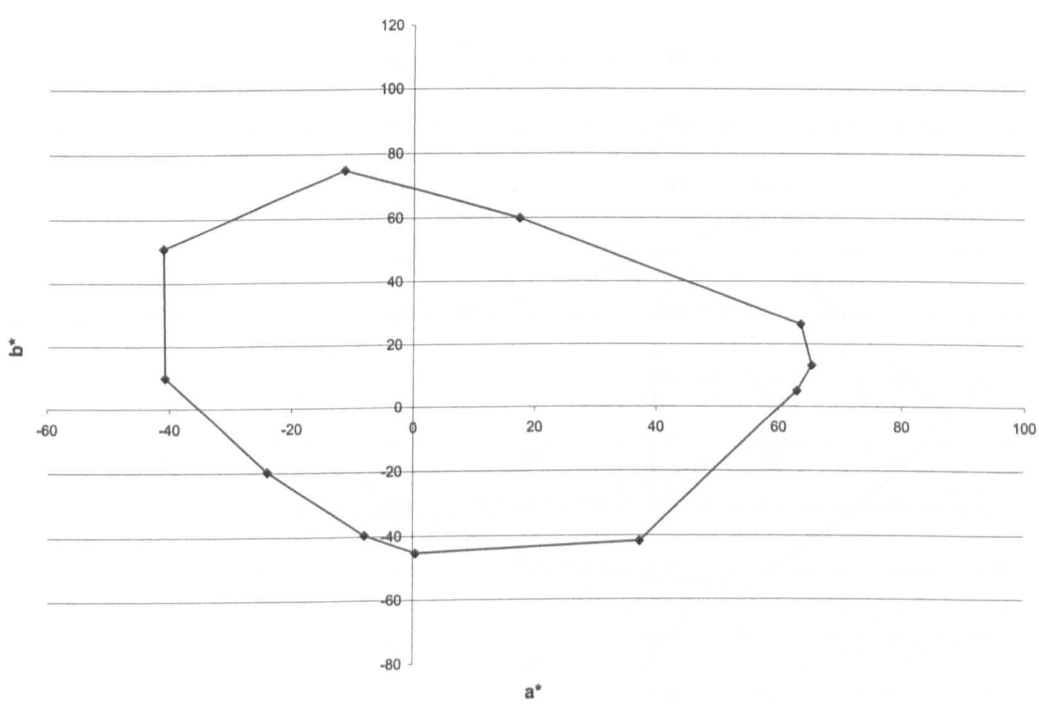
N.7 Plot showing the colour gamut of the Epson Pro 9000 ink set printed on Somerset Velvet paper (3.3).



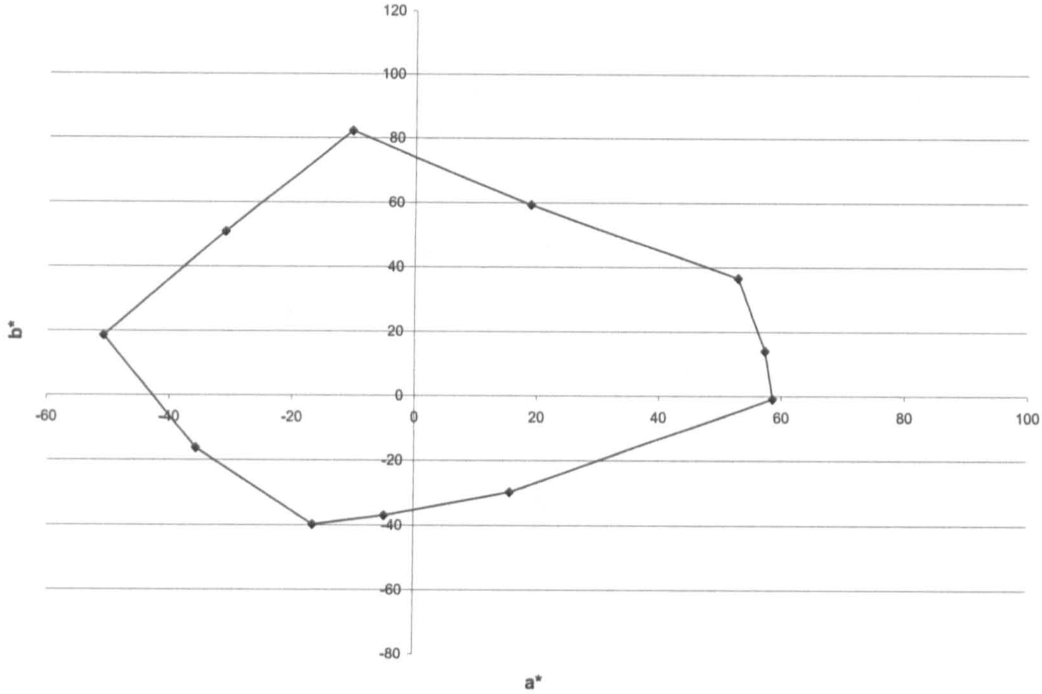
N.8 Plot showing the colour gamut of the Epson Pro 9000 ink set printed on Whatman paper (3.4).



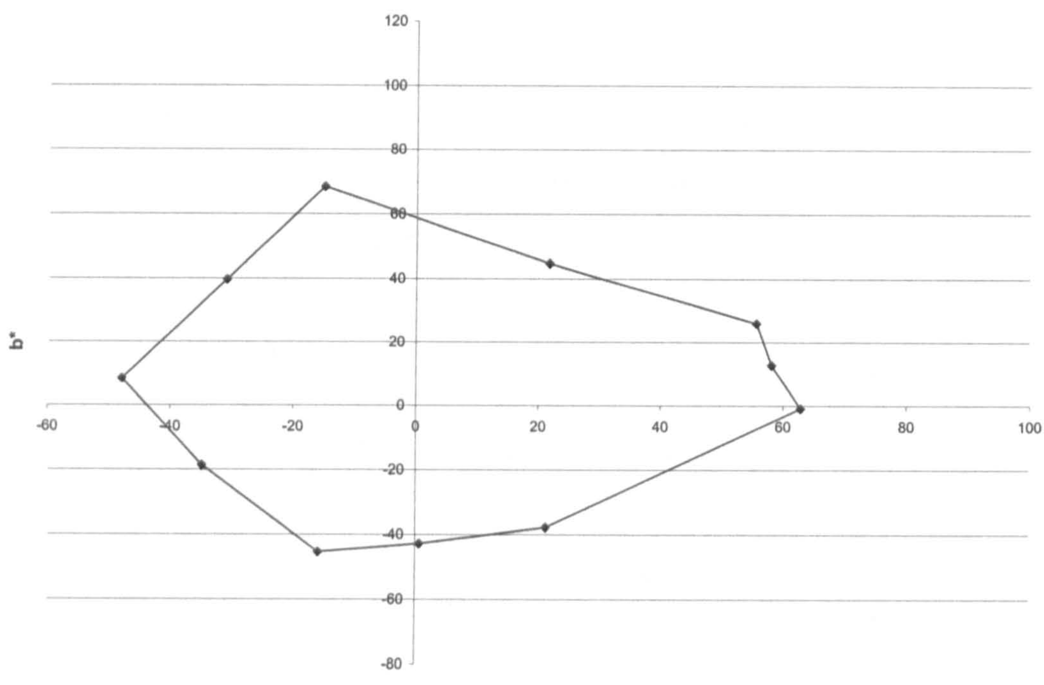
N.9 Plot showing the colour gamut of the Epson Pro 9000 ink set printed on Presentation Matt paper (3.5).



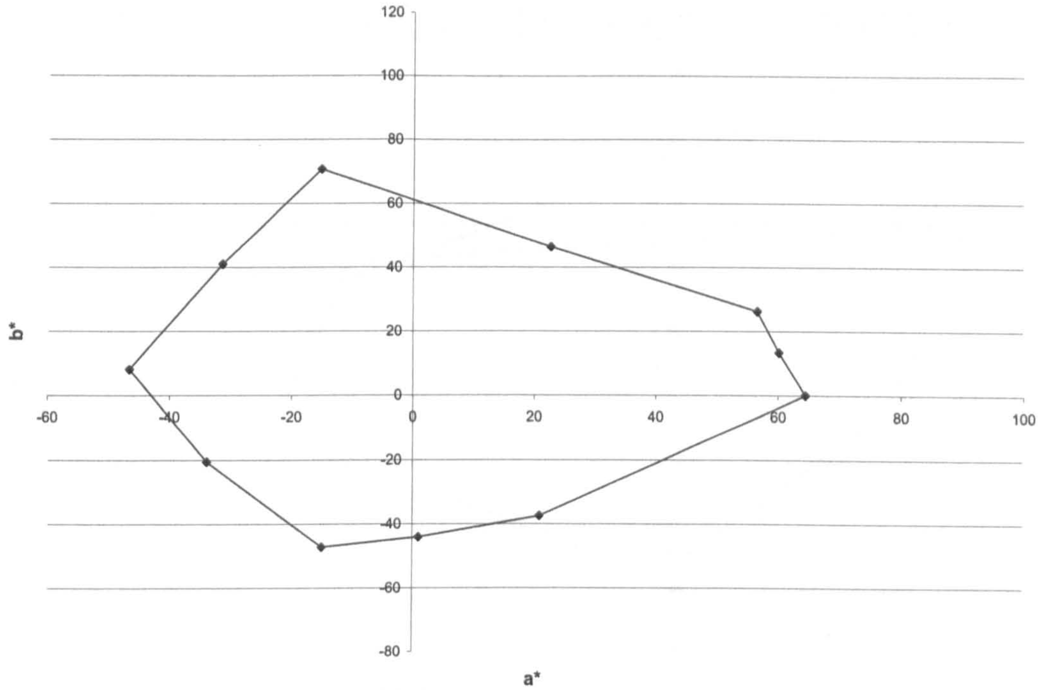
N.10 Plot showing the colour gamut of the Epson Photo Stylus ink set printed on Epson Photo Stylus Glossy paper (3.6).



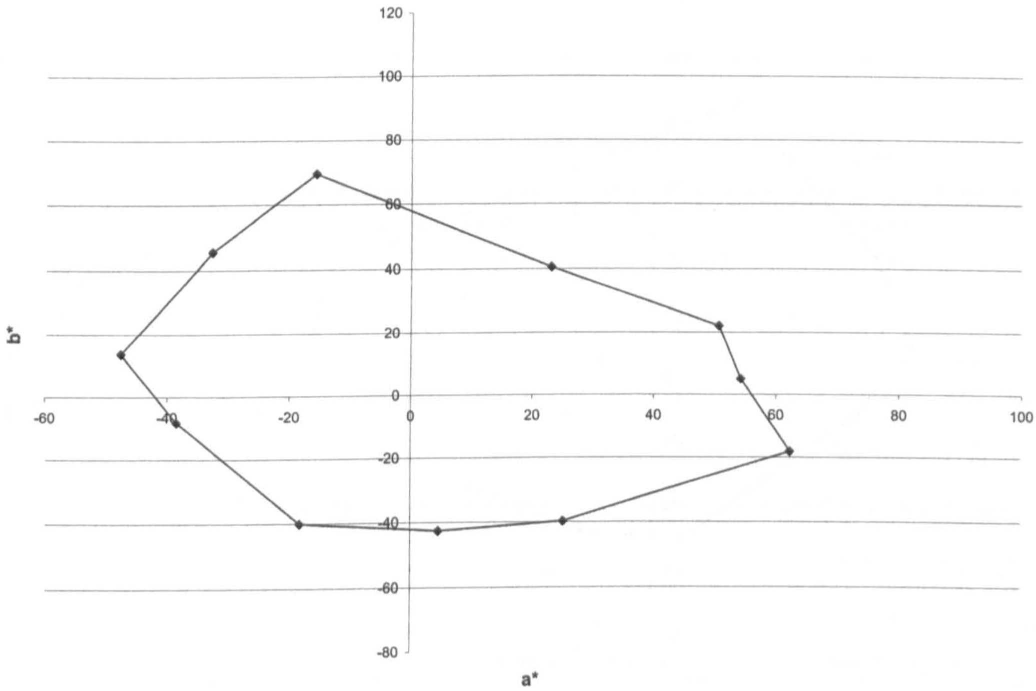
N.11 Plot showing the colour gamut of the HP 3500 ink set printed on HP Heavy Weight Coated paper (4.1).



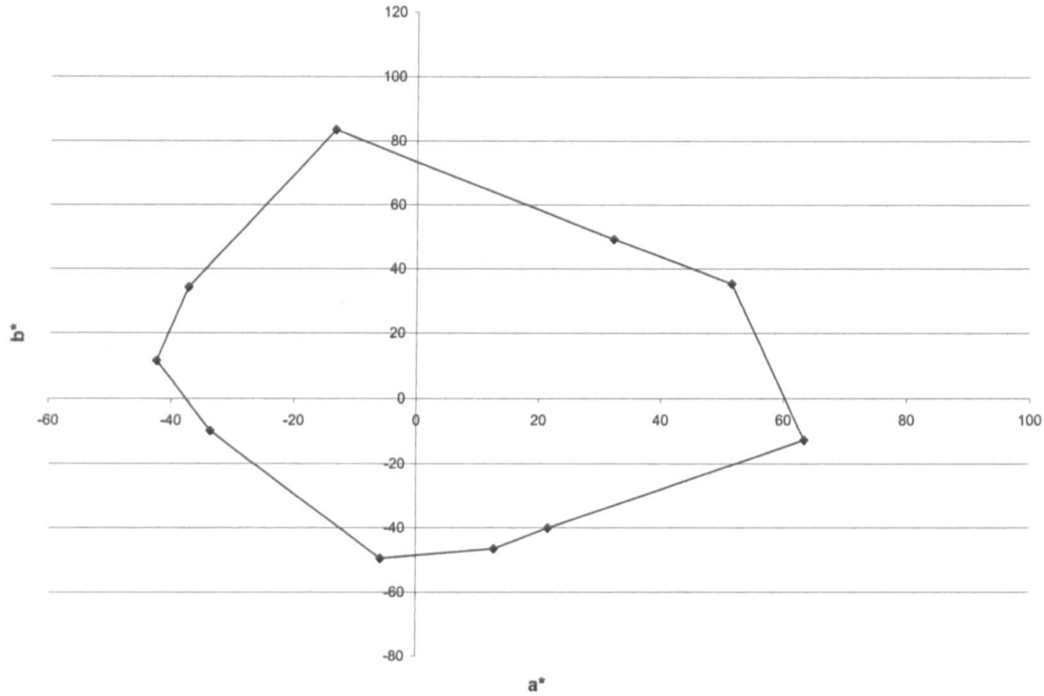
N.12 Plot showing the colour gamut of the Canon 1150 laser toner printed on Canon Ultra White paper (5.1).



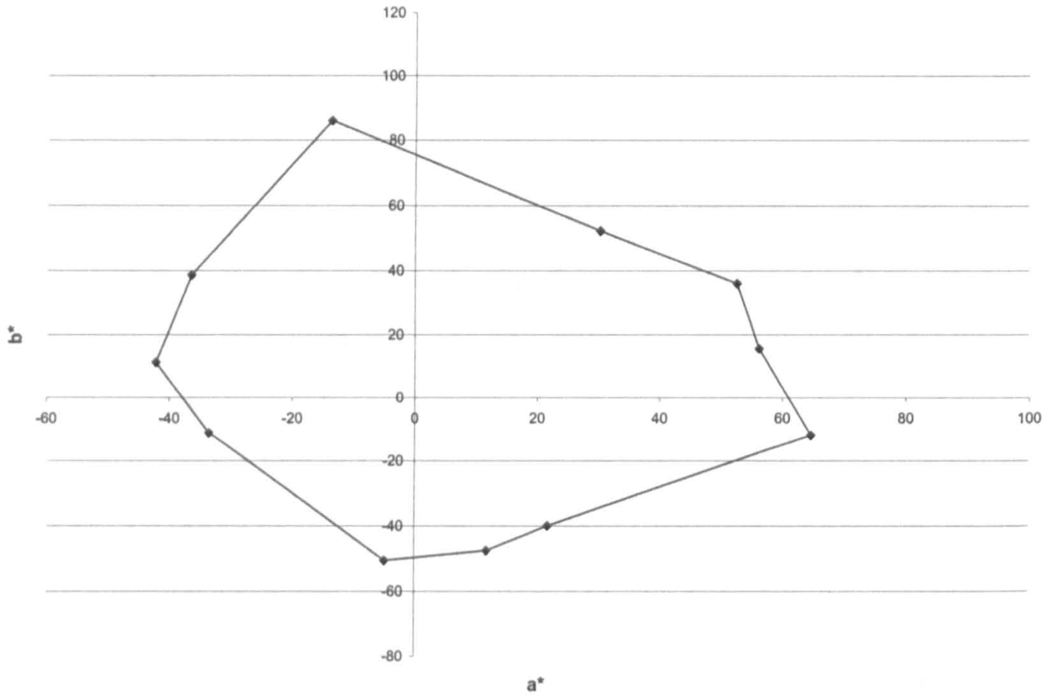
N.13 Plot showing the colour gamut of the Canon 1150 laser toner printed on Canon Card (5.2).



N.14 Plot showing the colour gamut of the Canon CLC 900 laser toner printed on Canon Ultra White paper (5.3)

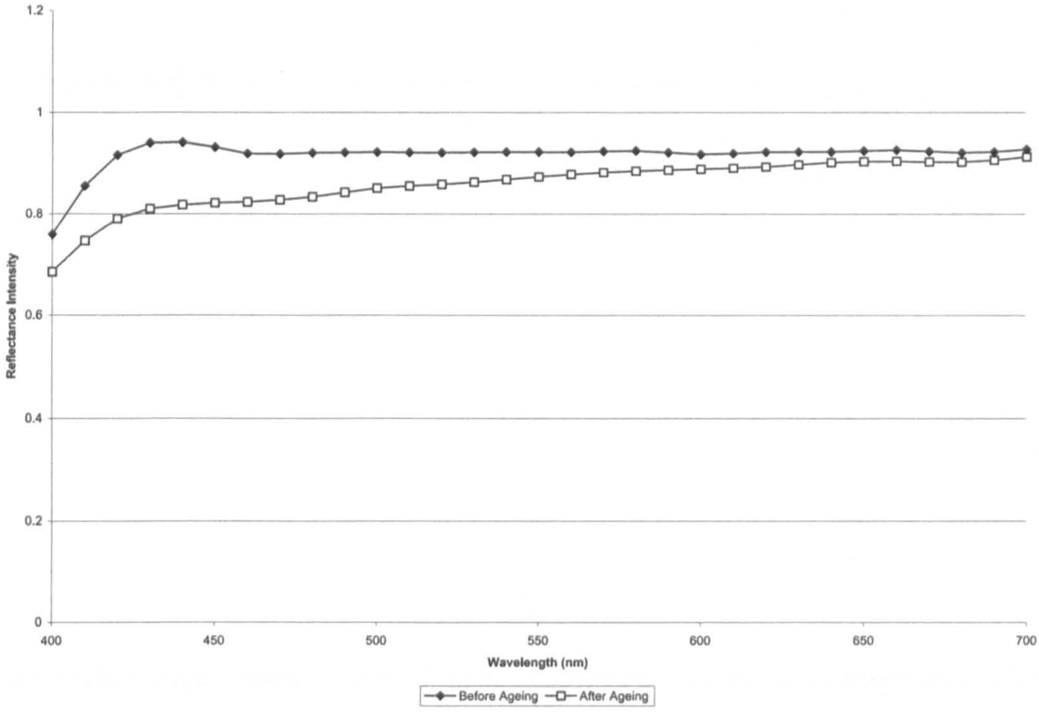


N.15 Plot showing the colour gamut of the Canon CLBP 460PS toner printed on Canon Ultra White paper (5.4).

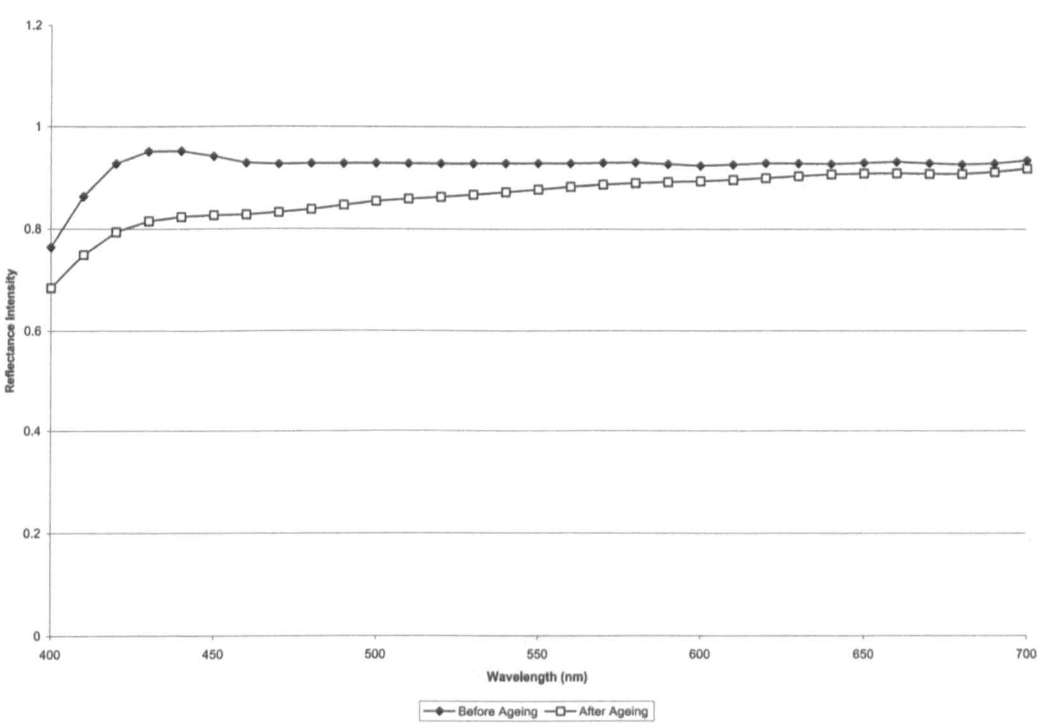


N.16 Plot showing the colour gamut of the Canon CLBP 460PS laser toner printed on Canon Card (5.5).

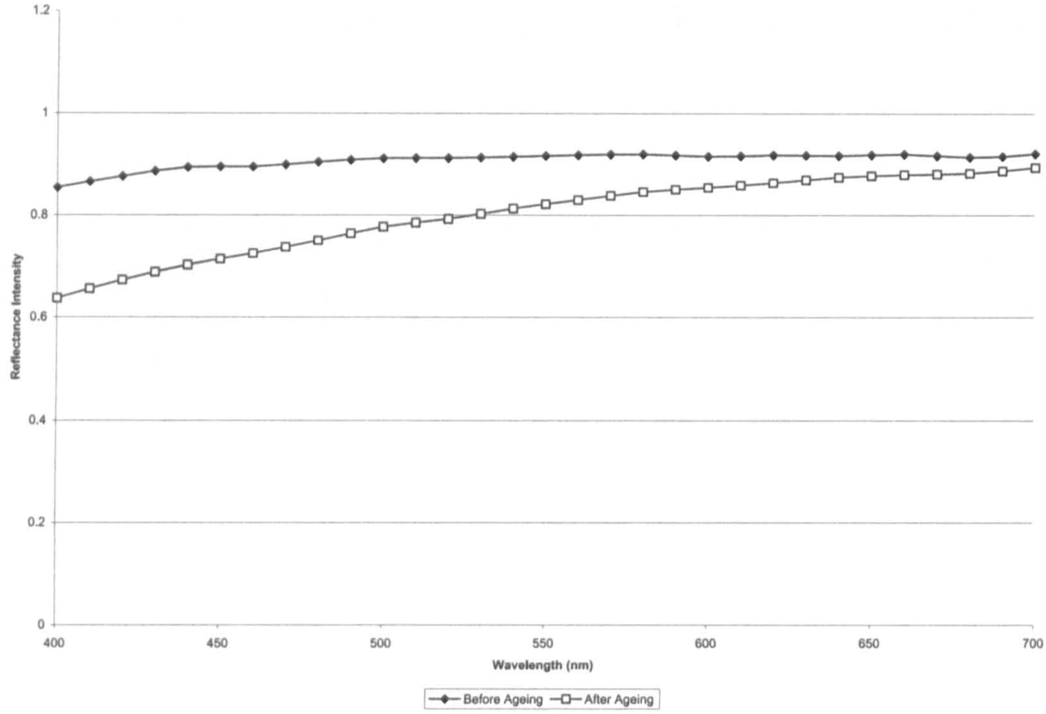
APPENDIX O - Thermal ageing spectral reflectance graphs



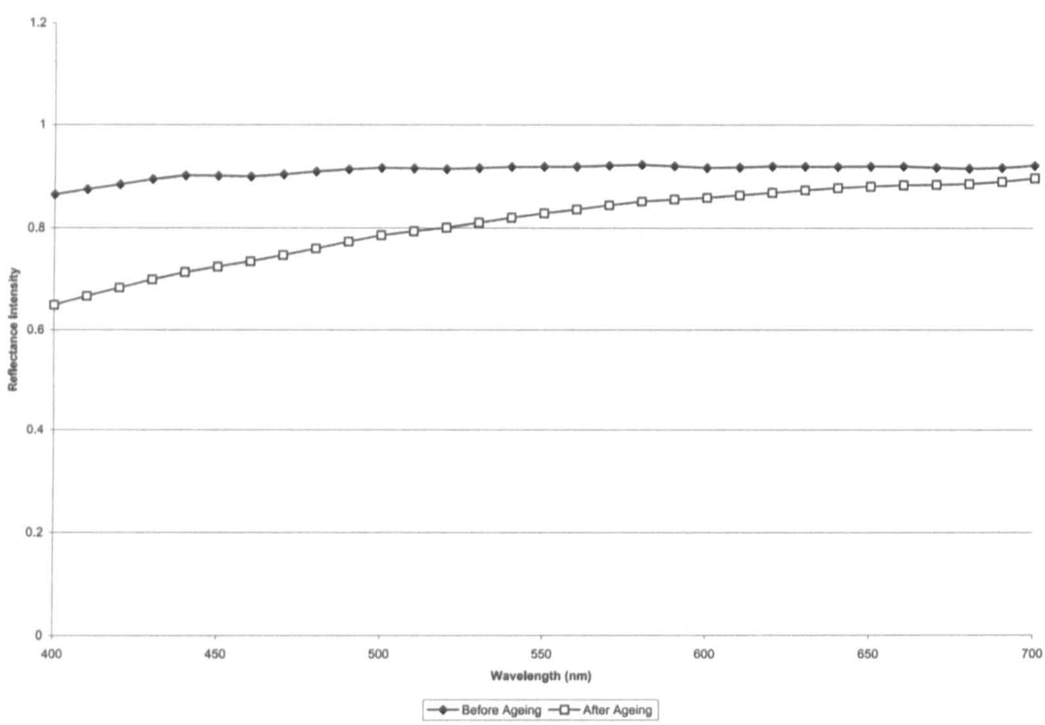
O.1 Plot showing the change in spectral reflectance of the Somerset Velvet paper (Recto) after thermal ageing.



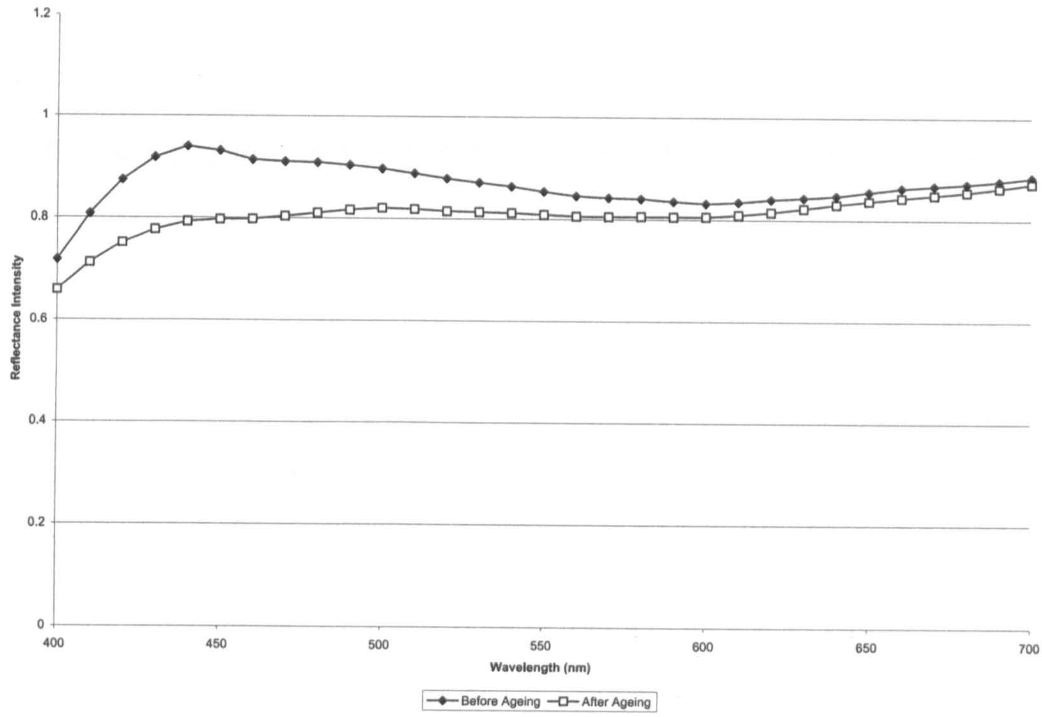
O.2 Plot showing the change in spectral reflectance of the Somerset Velvet paper (Verso) after thermal ageing.



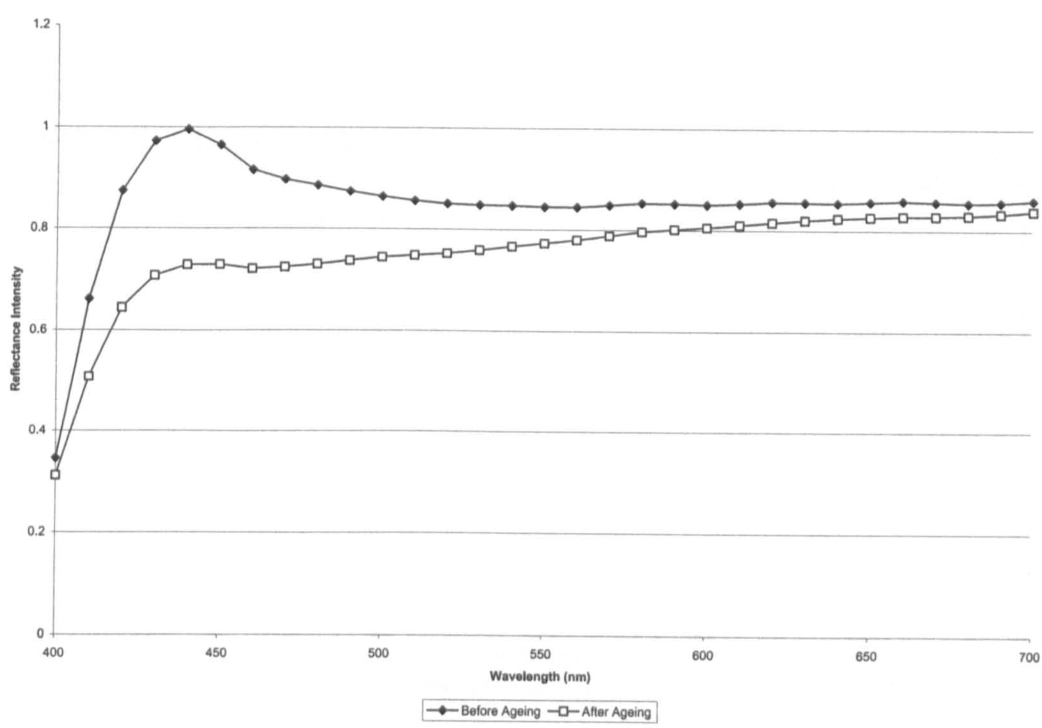
O.3 Plot showing the change in spectral reflectance of the Whatman watercolour paper (Recto) after thermal ageing.



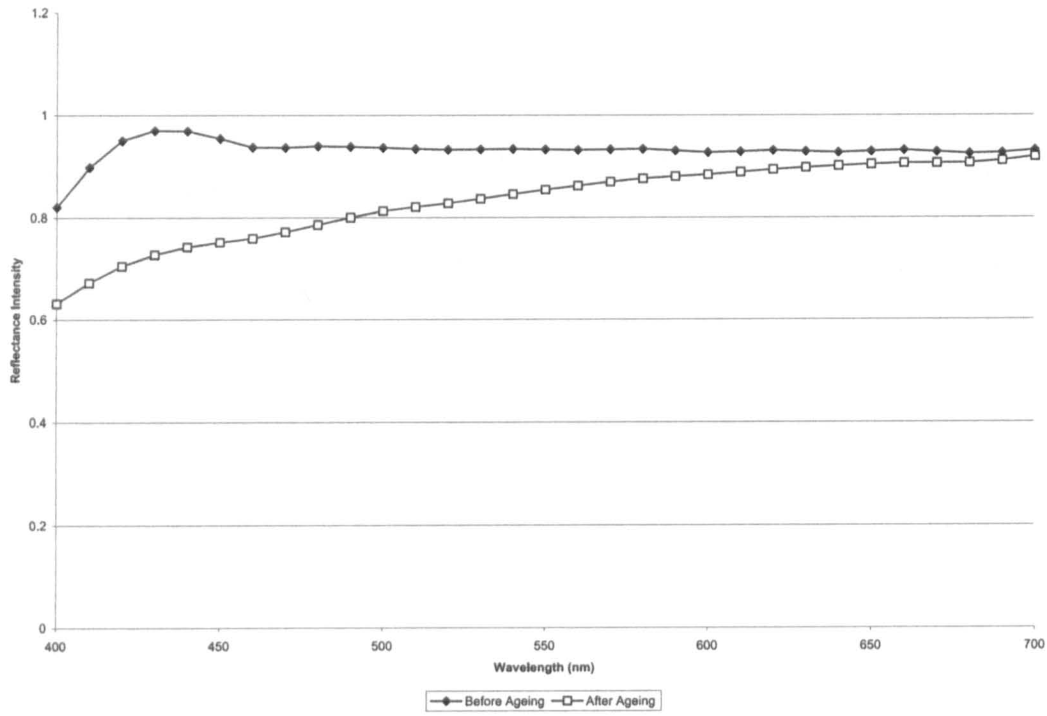
O.4 Plot showing the change in spectral reflectance of the Whatman watercolour paper (Verso) after thermal ageing.



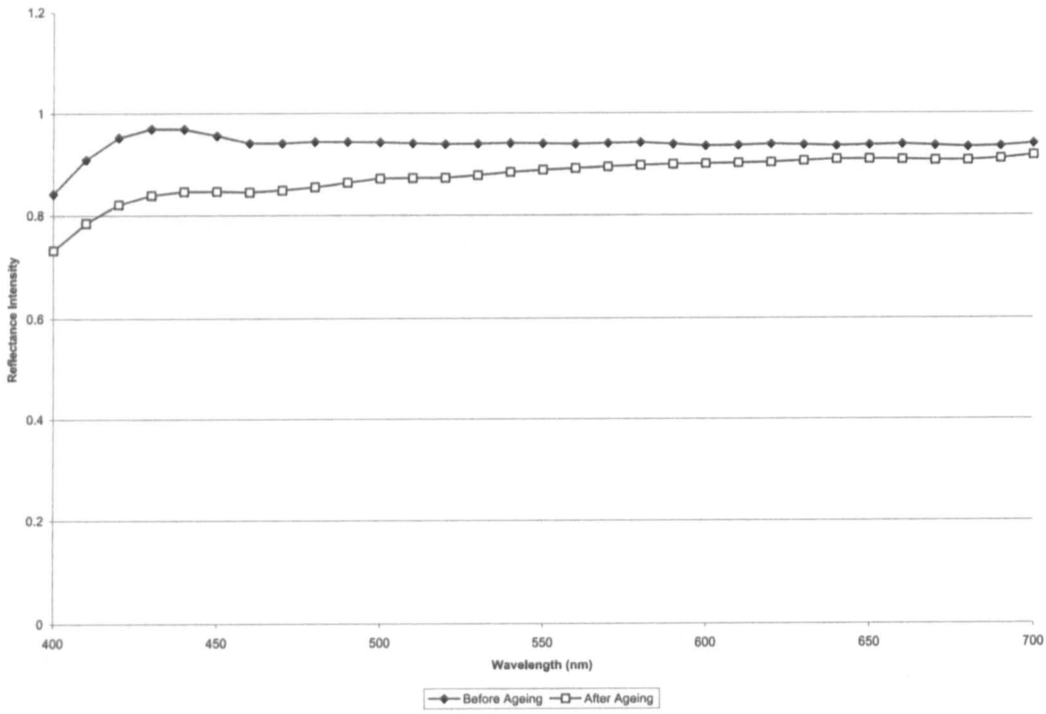
O.5 Plot showing the change in spectral reflectance of the ISVE paper (Recto) after thermal ageing.



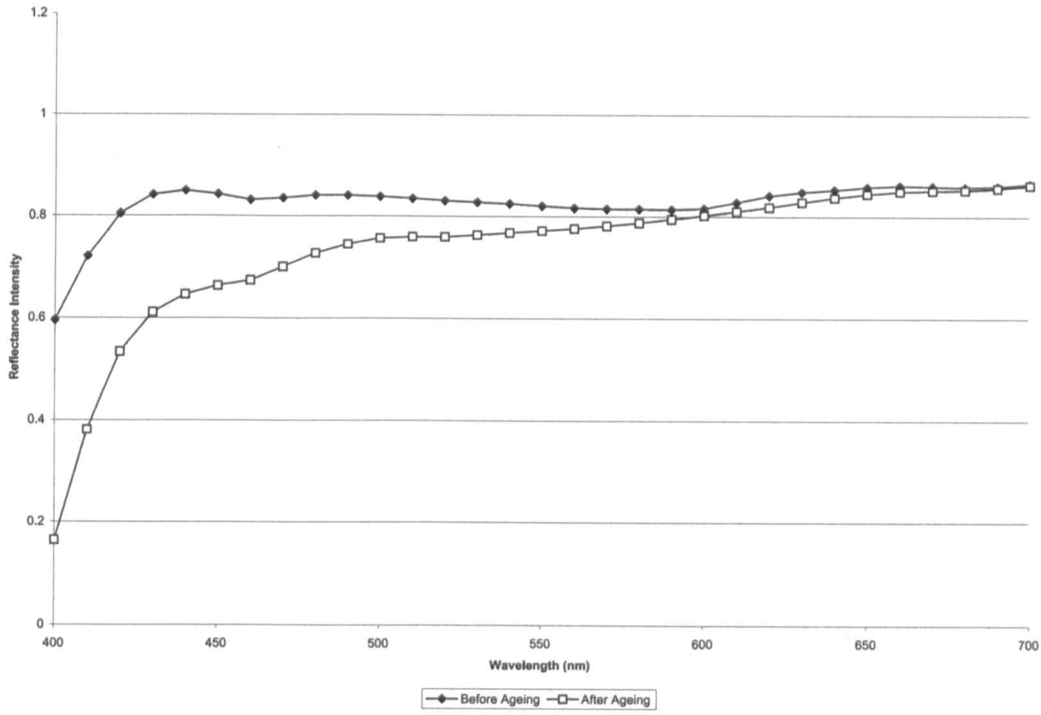
O.6 Plot showing the change in spectral reflectance of the ISVE Velvet paper (Verso) after thermal ageing.



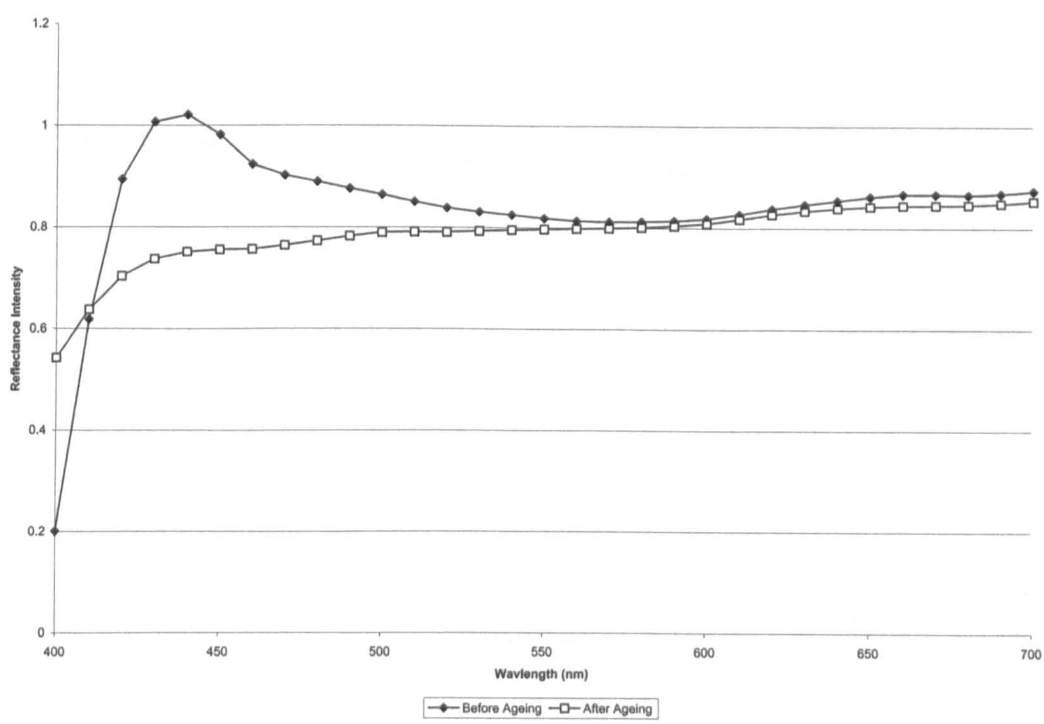
O.7 Plot showing the change in spectral reflectance of the Epson Presentation Matt paper (Recto) after thermal ageing.



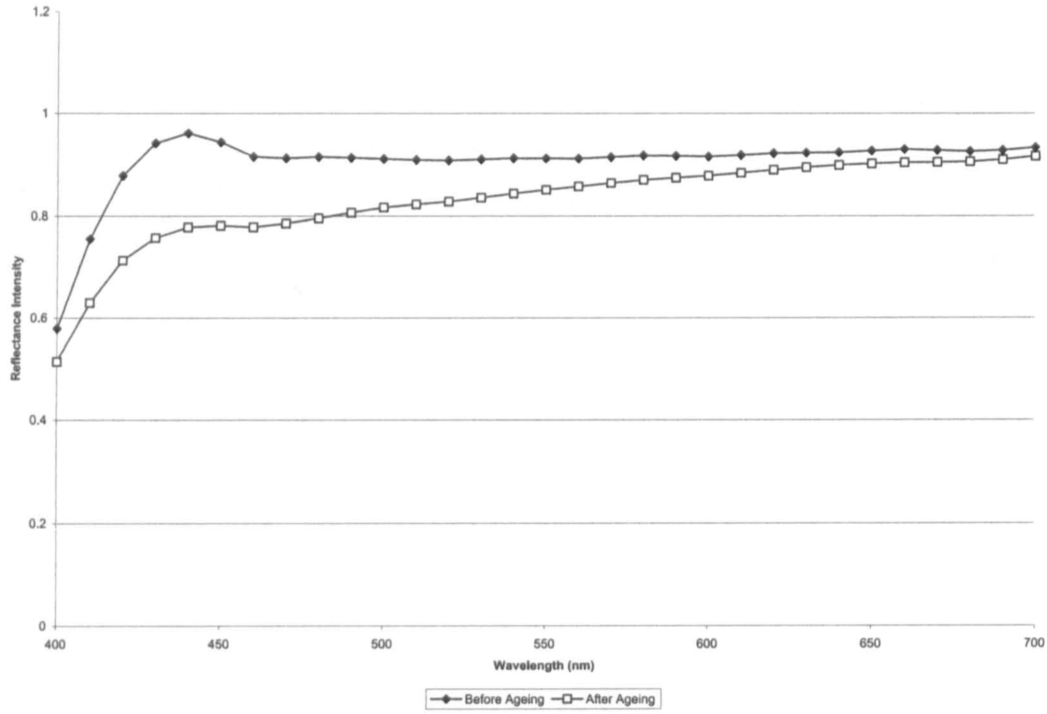
O.8 Plot showing the change in spectral reflectance of the Epson Presentation Matt paper (Verso) after thermal ageing.



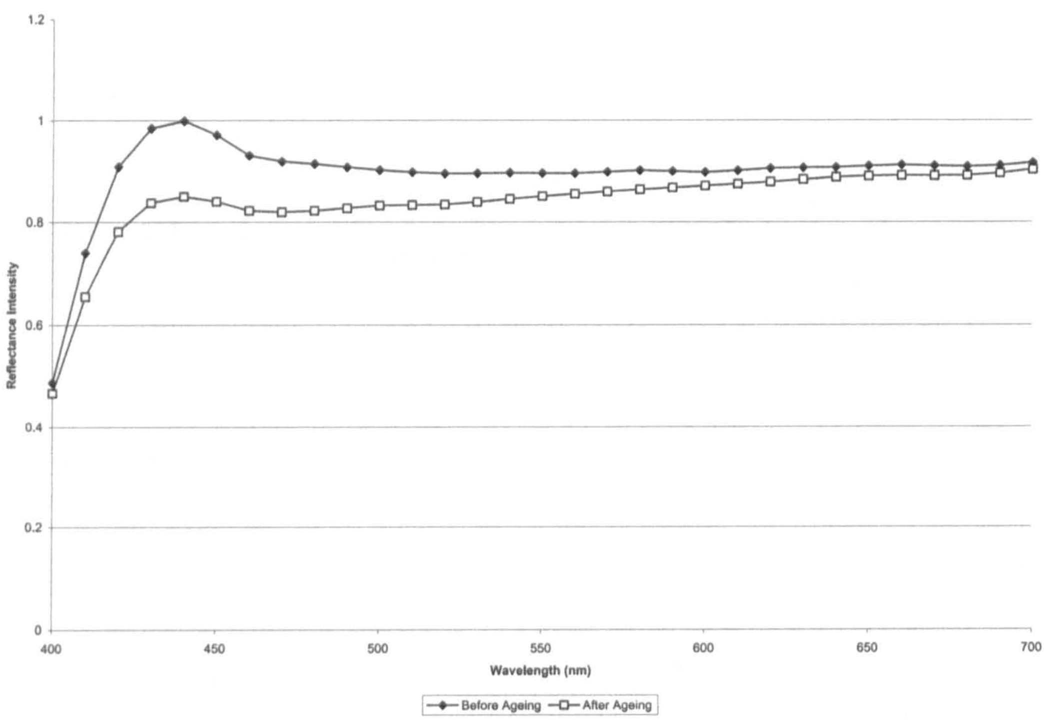
O.9 Plot showing the change in spectral reflectance of the Epson Photo Stylus paper (Recto) after thermal ageing.



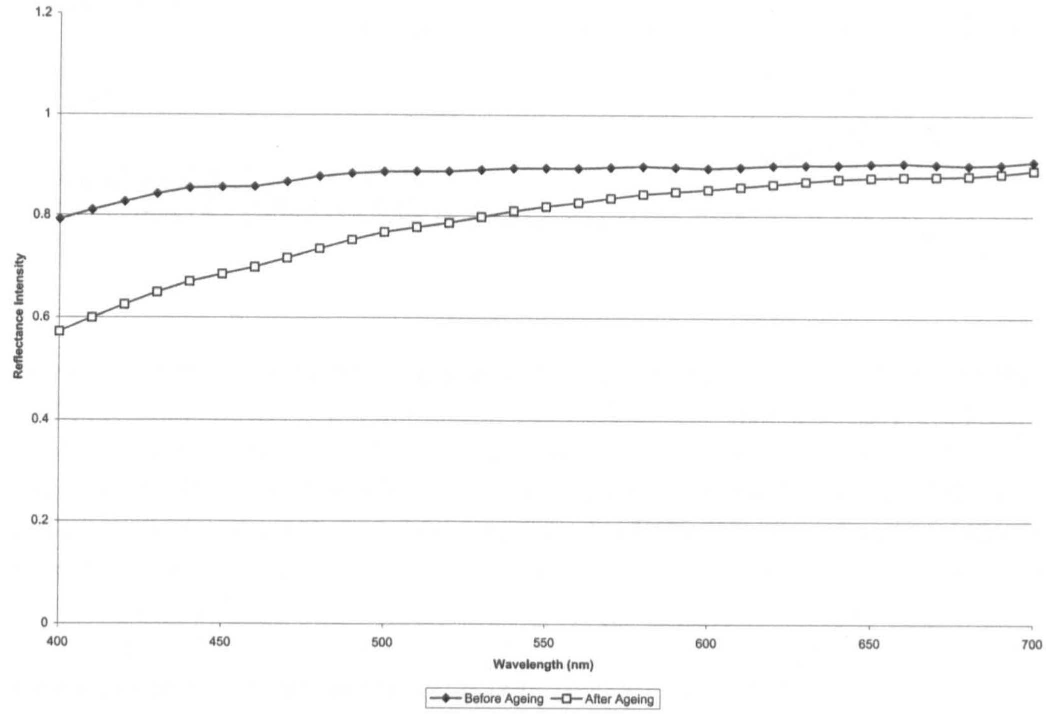
O.10 Plot showing the change in spectral reflectance of the Epson Photo Stylus paper (Verso) after thermal ageing.



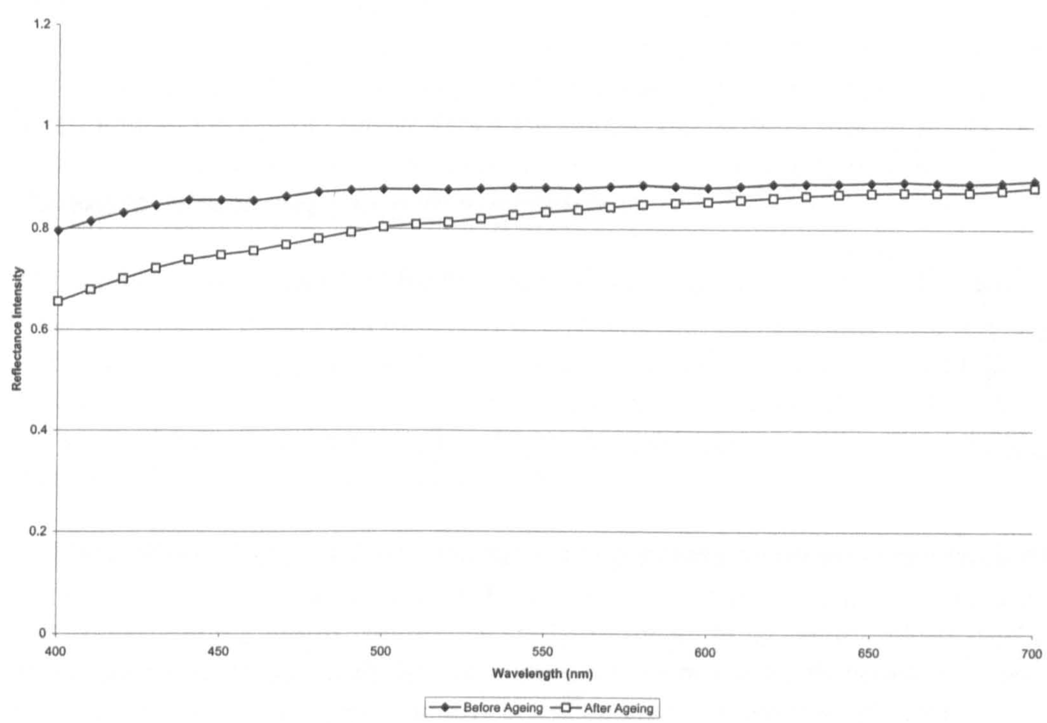
O.11 Plot showing the change in spectral reflectance of the Lyson Soft Fine Art paper (Recto) after thermal ageing.



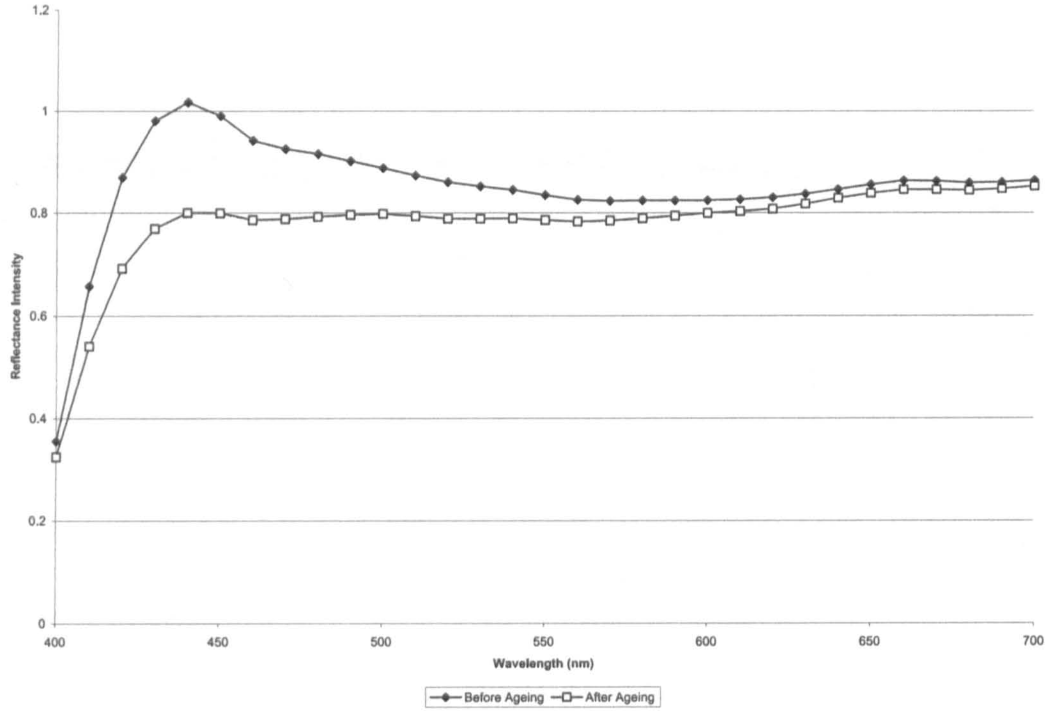
O.12 Plot showing the change in spectral reflectance of the Lyson Soft Fine Art paper (Verso) after thermal ageing.



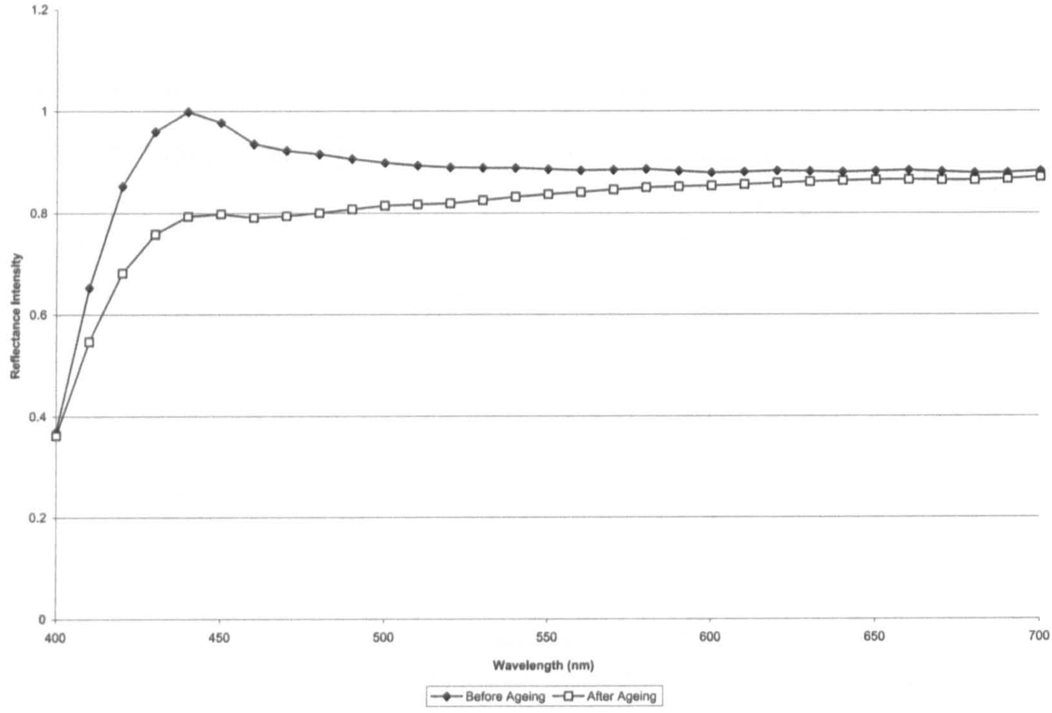
O.13 Plot showing the change in spectral reflectance of the Lyson Rough Fine Art paper (Recto) after thermal ageing.



O.14 Plot showing the change in spectral reflectance of the Lyson Rough Fine Art paper (Verso) after thermal ageing.



O.15 Plot showing the change in spectral reflectance of the HP Heavy Weight Coated paper (Recto) after thermal ageing.



O.16 Plot showing the change in spectral reflectance of the HP Heavy Weight Coated paper (Verso) after thermal ageing.

APPENDIX P - Articles published during the research project

P.1 Reference

Glynn D. (1998) The preservation and conservation of non-impact printing materials, Printmaking Today, Vol. 7 (2), p. 31.

The Preservation and Conservation of Non-Impact Materials

Non-impact prints have become a prevalent and accepted form of fine art printmaking. There have been a number of exhibitions this year that have contained such prints, and galleries, like the Tate Gallery, have begun to receive these prints into their collections. There has also been an art group established in California, called the International Association of Fine Art Digital Printmakers (IAFADP), which has been set up to improve the standards of digital printmaking. With the continuing development of this area, there is growing concern among printmakers, paper conservators and curators, about the stability of these prints. It has been found that they are very sensitive to both light and moisture.

The term "non-impact", also referred to as "NIP", is the name given to describe printers that transfer ink to paper without striking the substrate. This class of printers includes: electrophotography; ink jet; thermal imaging; photochemical systems; toner printing; laser printing; etc. Non-impact prints were not designed to last, as the printers were made to produce ephemeral graphics or proofs, using inks and media of very poor quality. Since the production of these fine art prints, printer companies are researching into improving the lighfastness of their inks, and have already introduced inks with better lightfastness.

The media or paper supplied for the printers also causes concern, as the resin coating on some papers can turn yellow after exposure to daylight for a few days. The media is also very sensitive to water, and can easily be damaged with the slightest amount of moisture. However, it has been found that printmakers are not content with the final finish that the media produces, and are now using good quality watercolour and printmaking papers.

At Camberwell College of Arts, we have set up a research program to identify the problems that these new printing technologies could bring to paper conservators and curators in the future. We will be studying the archival quality of the prints, including the lighfastness of the inks and media supplied for the printers. The research will also study print identification, and investigate the effect various conservation treatments will have on the prints. The research will also study an ethical argument which has developed with the conservation of computer generated prints. We will be asking whether it is necessary to conserve the original print, if damaged, when another identical print can be reproduced with the computer file.

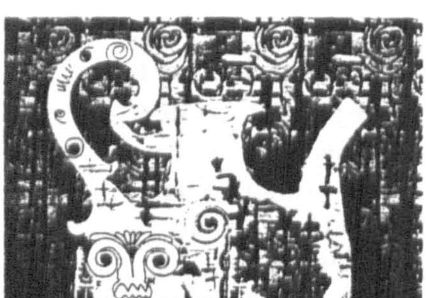
Research

Materials for large format ink jet printmaking

Information and advice by George Whale and Debbie Glynn

In the US, serious digital printmaking is increasingly dominated by the IRIS printer, a high resolution, continuous flow ink jet device. The superb quality of prints produced by David Adamson Editions (see Jack Miller's interview in *Printmaking Today*, 7, No. 2), Muse [X] Editions and other 'digital ateliers' has encouraged leading artists like Jim Dine, Robert Rauschenberg and Chuck Close to use and endorse the medium. This has led to a slow but accelerating infiltration of IRIS 'Giclée' prints into the commercial art market and into the galleries and collections of prestigious institutions such as the British Museum, the Getty Museum, the Guggenheim and MOMA.

Unfortunately the equipment is extremely expensive. The diligence needed to maintain and run it, and the high level of software expertise required, means that artists using IRIS printing are heavily dependent on experts to guide them through the maze of technology. As a result large Giclée prints can cost as much as £200 apiece. Increasingly, in Britain and elsewhere, lower-cost alternatives – medium or large (wide) format 'drop-on-demand' ink jet printers manufactured by ENCAD, CalComp, Epson and others for use in the graphics industries – are being acquired by art schools, print studios and individual artists. Although these devices are relatively easy to run and maintain, and robust enough to encourage experimentation, consistently high quality printmaking depends upon a thorough understanding of materials, their properties and usage. This article, based on over three years' experience of using an ENCAD Novajet III A0 colour printer at Camberwell College of Arts, London, UK, reviews the technology, with particular reference to inks and substrates.



Vessel Series, by Charlotte Hodes. Ink jet print.

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Varieties of ink jet

There are three different types of ink jet printer on the market today: continuous ink jet; drop and demand; and thermal/bubble ink jet. All three systems rely on a stream of fine uniformly shaped droplets of ink, controlled by a digital electronic imaging source, to produce images *directly* on the page. The printers differ by the technology used to generate the droplets, which determines the droplet size and number. The quality of the printer is governed by the number of droplets or dots per inch (dpi) it can produce, known as the resolution. Ink jet resolution can range from 300 to 1800 dpi, depending on the printer. 1800 dpi is achieved by an apparent resolution value, where the individual dot can be varied from 0 to 32 droplets per dot.

The high quality printers like the IRIS use the continuous ink jet (CIJ) technology. The printer employs very fine nozzles to issue a continuous stream of very fine ink droplets. Up to one million droplets can be produced per second, and the diameter of each droplet can be as small as 15 microns. The stream of ink forms an image by giving the unwanted droplets an electrical charge, which are then deflected away from the stream when it passes over a deflection field. The deflected ink is either recycled or thrown away.

Drop on demand (DOD) printers are much cheaper to produce and maintain than CIJ systems, but printing speeds are slower and image resolution is lower. The system ejects droplets from a nozzle only when they are required. The systems disperse ink at rates of 0 to 4000 drops per second, and use larger nozzles which produce droplets typically 50 to 100 microns in diameter. Thermal/bubble jet printers use a heating element to produce droplets of ink on demand. The systems are at the lower end of the market and are most favoured by offices and homes to produce reasonable graphics.

Colour and light fastness

Ink jet printers use four coloured inks to produce all the colours: cyan, magenta, yellow and black (often abbreviated to CMYK). When the four colours are overlaid they can produce up to 16 million different colours.

Ink jet systems require a fine fluid ink so that it may pass through the nozzles. CIJ systems can only use water-based inks that contain organic soluble dyes to avoid clogging the fine nozzles. The dyes used are often modified from textile dyes because of their colour reliability, their solubility in an aqueous medium, and their thermal stability. Other ingredients such as solvents, the most common of these being glycol, are added to the inks to lower the evaporation rate and to allow the ink to penetrate more rapidly into the paper. DOD printers can use water-based dye inks and solvent-based pigmented inks (made up of larger sized particles), because their nozzles are wider. However, it is considered by printmakers that the pigmented inks do not have the same vibrancy as the dye-based inks.

The dye-based inks have limited lightfastness and water resistance. Previous research has shown that ink jet inks can last from 6 months to 50 years, according to the ink and paper type used. Therefore, it is always good policy to keep ink jet prints away from strong light. At Camberwell, we are researching an important relationship between the ink and paper. We believe that the substrate is very important in determining whether an ink is lightfast, with uncoated papers such as printmaking and watercolour papers having better lightfastness results than coated ink jet papers.

To maximize the life of ink jet cartridges (and thereby reduce running costs), they should be cleared at the first sign of any blockage. As always, the least scientific method is the best – with some types of cartridge, blowing hard into the vent at the top often does the trick, by forcing ink through the apertures. Isopropyl alcohol swabs, available from chemists' shops, are excellent for cleaning the contacts and, left in contact with the printhead for ten or 15 minutes, can help to clear stubborn blockages. Some cartridge types can be refilled five or six times before apertures start to become irretrievably blocked – even then they can be put to good use in testing inks that have been specially mixed to match a spot colour or watered down or modified, to achieve a particular effect.

Murphy's second law of printmaking states that even the most impermanent inks become permanent on contact with expensive clothing. Ink suppliers provide rubber gloves, refill cells and special syringes to prevent you turning your studio into a Tarantino film set.

Substrates

Commercial papers

Specialist ink jet coated papers play an important role in determining the image quality in ink jet printing, as quality is determined by the paper's ability to control the ink drop. The coating aids printing quality in several ways by: preventing the liquid ink from being absorbed too far into the substrate by holding it near the surface; deterring the ink from feathering along the paper fibres (dot gain); improving colour saturation; improving ink drying time; causing minimum cockle and curl to occur. There are several different types of coated paper available for ink jet printers, including gloss, semi-gloss and matt surface papers of different weights.

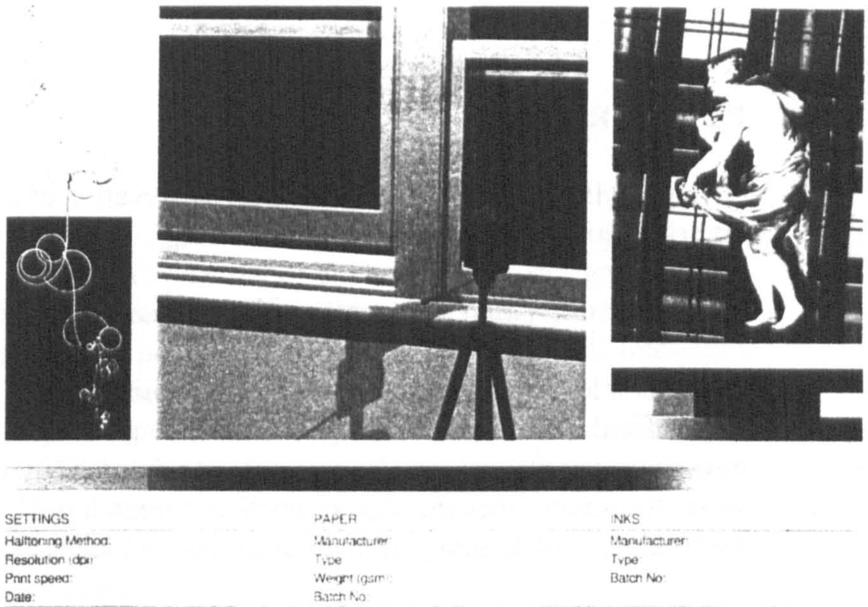
Particular care needs to be taken with the framing/mounting of coated papers. Large sheets under 200 grams in weight have a tendency to 'sag' when floated or window-mounted, and the hydrophilic (water-attracting) nature of the surface can cause problems if the print is placed in contact with glass or perspex. Some digital print bureaux offer new forms of dry mounting and encapsulation (sealing the print within clear plastic laminate) ideal for medium-term display and storage.

Ordinary cartridge papers can also be used. Excellent low-cost positives, for photo-etching or photo-stencil, can be made by printing in black onto 80 gram cartridge, increasing exposure times (by a factor of five or six) to compensate for the paper's opacity.

Fine art papers

Where prints are to be sold, artists surely have a duty to ensure permanency, and commercial coated papers are not designed for extended use – at worst, they can yellow, buckle, fade or become frangible in a matter of weeks. Good quality fine art papers on the other hand, are tried and tested, contain few chemical agents to react with the inks, come in a wide range of weights and finishes, can be framed without difficulty and, as mentioned above, they improve the lightfastness of the image.

Natural papers, lacking artificial whiteners, will tend to impart a creamy or yellowish tint to the print, which can be 'corrected' by subtly shifting the colour balance of the digital source image towards blue or purple. High absorbency can result in a loss of colour intensity, cause excessive dot gain (lightening the image can often fix this). Low absorbency on the other hand (e.g. in hot-pressed papers) may cause ink to 'pool' on the surface. Thin papers often buckle due to the water content of the inks, especially at higher print speeds (since the print has less time to dry between passes), whereas excessively thick papers can scuff against the printheads.



Test image for ink jet print.

Somerset and Arches have produced sized fine art papers to overcome many of these problems. Although designed for IRIS printing, these might well be compatible with other types of printer.

Remember: some ink jet printers are designed for use with 'A' sizes (A0, A1, A2, etc.), and are not always easily adaptable for use with imperial sizes – check this before ordering your paper, indeed, before ordering your printer!

Test prints

A good practical way to establish the characteristics of materials is by making trial prints from a test image such as the one shown, containing neutral grey areas (centre) to reveal any colour casts caused by the paper or by ink variations, skin tones (top right) which are often the most difficult to render accurately and a line drawing (left) to reveal any problems in the printing of fine line art (especially white on black, where 'filling in' is often a problem). A band of spectral colours is useful in comparing different papers for loss of intensity. Dot gain, which is most likely to occur where saturated colours or black regions adjoin, can also be tested for, although bear in mind that moderate dot gain is often desirable for softening unwanted 'graininess'. Space should also be reserved in the test image for recording printer settings and materials specifications.

Most devices offer some control over print speed and ink flow, both of which can affect the performance of a paper. Because ink jet is a non-contact process, the texture of substrate is rarely an issue and can often be used to good effect. At Camberwell we have successfully used most types of Somerset, Fabriano and Whatman papers, also Arches, Rivoli, heavy cartridge papers and primed canvases. For longevity, always print on a good quality, acid-free rag paper around 150-300 gram, using inks with improved lightfastness.

Other factors affecting the quality and durability of ink jet prints include the quality and resolution of the source image, management of colour, proofing and editioning procedures, ambient temperature and humidity and, the choice of the printer itself.

Ink jet supplies/services

RES Digital Imaging Solutions: Crown House, The Metro Centre, Toutley Road, Wokingham, Berkshire RG41 1QN, UK. Tel: +44 (0)118 977 1866 Fax: +44 (0)118 977 1420.
(All ink jet printer types).

Gammadata Ltd: The Business Design Centre, Studio 107, 52 Upper Street, Islington Green, London N1OQH, UK. Tel: +44 (0)171 288 6136 or +44 (0)171 288 6145; Fax: +44 (0)171 288 1985 (Agfa, Fuji, Hewlett Packard, Kodak, Tektronix).

Hewlett Packard produce a booklet called *Printing Materials Guide for the HP DesignJet printers* which lists their media, endosed media, and non-endosed media including various coated papers, films, textiles etc., made by different manufacturers.

Contact: Debbie Glynn, Camberwell College of Arts, School of Art History and Conservation, Wilson Annexe, Wilson Road, London SE5 8LU, UK. Tel: +44 (0)171 514 6433; Fax: +44 (0)171 514 6405.
email: dglynn@camb.linst.ac.uk

P.2 REFERENCE

Glynn D. (1999a) The preservation and conservation of computer generated fine art prints, Imprint, Vol. 34 (1), p. 16.

The preservation and conservation of computer generated fine art prints

Considerable progress has been made in establishing new methodolgies and techniques for the fine artist working with the emergent digital technologies. There is now an urgent requirement for research into the stability if this new form of art work. At present, there has been very little research published on the durability of the produced work, in regard to both the ink and the substrate.

At Camberwell College of Arts we have set up a research program to identify the problems that these new printing technologies could bring to paper conservators and curators in the future. The aim of our project is to i) establish the archival quality of computer generated produced materials and ii) to identfy possible conservation problems associated with this type of material, and to propose treatments to deal with these. Since artists have exploited mostly ink jet and electrophotographic printed materials in their work, the research will focus on these areas of printing.

Concern for the stability of digital prints rose after it was found that the inks used to produce the very first large format ink jet prints, were fading when exposured to light, after only a few months. The archival quality of the inks and papers supplied for the computer printers had initally not been a factor for the manufactures, because their printers were intended to produce ephemeral graphics and proofs. Research has now been undertaken by manufactures to develop better quality inks, papers and printers. This research has led to the availability of a higher standard of media and hardware, and manufacturers are constantly introducing better media onto the market.

Both ink jet and electrophotographic printers rely on specialised inks and papers for high quality output. Out of all the digital printing technologies ink jet systems are the most dependent on the type of ink and paper used with the printer for good quality imaging.

The ink jet printers require a fine orifice from which a tiny stream of uniformly shaped droplets of ink spurt out directly onto the paper surface. These nozzles require a very fine fluid ink so that it may pass through the orifice. Water-based inks, coloured with organic soluble dyes are the inks used for these printers. Most of the dyes used are modified from textile dyes because of their colour reliabilty, their ability to be soluble in an aqueous medium, and their thermal stability. The use of a water based dye ink means that the prints produced a highly unstable to light. Some ink jet printers have slightly larger nozzles and can use more stable pigmented solvent based inks, but the resolution of the images are not as high and artists have said that the colours produced are not as vibrant as the dye based inks.

The liquid ink requires a specially coated paper to prevent the ink from being absorbed too far into the substrate. These coatings are composed of pigments, latex, fluorescent agents and a small quantity of binders, and are designed to have a very porous structure so that most of the ink is absorbed near the surface of the paper. The coatings are poorly held onto the paper, as only a smalll amount of binders can be used so that the paper remains porous. This means that the coating is easily damaged by the minimum of abrasion. The presence of latexes and fluorescent agents in the coating also cause the paper to yellow after exposure to ambient conditions. However, artists are also using good quality water-colour and printmaking papers, because they like the softening effect which is characterised by the ink flowing along the fibres.

Electrophotographic printers are based on the principle that ultra violet light destroys an electrostatic charge. A charged surface is selectively discharged by exposure to light. The remaining charge is used to attract a colourant, referred to as a toner, which is then fused onto a sheet of paper by heat and/or pressure. Electrophotographic printers do not have as much limitations as the ink jet media. The toners are made up of a solid mixture of fine resin coated pigments, but some toners also contain a combination of pigments and dyes.

Alongside the secind stage of the project, additional research will be undertaken to explore a philosophical argument which has arisen with the topic of computer generated printed material conservation; namely, whether conservation treatment should be performed when the print can almost perfectly duplicated with ease.

P.3 REFERENCE

Hall S. and Glynn D. (1999) Richard Hamilton Book Review, Printmaking Today, Vol. 8 (2), p. 32.

Richard Hamilton, New Technology and Printmaking, Catalogue. Edition Hansjörg Mayer, London, 1998. In association with the Alan Cristea Gallery. 35pp. With 32 colour and monochrome illustrations. Available from the Alan Cristea Gallery, 31 Cork Street, London, W1X 2NU. £5.

Although Pop Art is now thought to have begun with Paolozzi's "I Was A Rich Man's Plaything" in 1947, the seminal work of this epoch is still believed to be Hamilton's "Just What Is It That Makes Today's Homes So Different, So appealing?" of 1956. It is this work, in a later incarnation, that makes its appearance, along with other key works from Hamilton's oeuvre, in a new show "New Technology and Printmaking" at the Alan Cristea Gallery.

100 years ago it was photography that offered the main challenge to traditional notions of artistic form and content. This show demonstrates, through a series of arresting self-portraits and interiors, that this honour may now have fallen to the computer. The computer allows contemporary practitioners to re-proportion, rearrange and rework images from a number of different contexts and sources in a way that was not previously possible. This has enabled artists such as Hamilton to explore the boundaries of art in terms of subject matter and stylistic expression without being hampered by the technical means of realisation.

Hamilton has realized, prehaps more than most artists before him, that there is a seamless relationship between the "old" technologies of etching, lithography, and screenprinting and the "new" technology of the computer. This is not just computer art, it is art made with computers.

P.4 REFERENCE

Glynn D. (1999b) The future is permanent, Printmaking Today, Vol. 8 (4), p. 31.

The future is permanent argues Debbie Glynn

Artichoke in ½, 1999, by Nic Barlow. Inkjet print using Epson 9000 printer. Image courtesy of Rebecca Hossack Gallery, London, UK

Inkjet inks have been criticized many times in the past for poor light stability, but the issue needs careful scrutiny. The inks for these printers can be either water-based dye inks or solvent-based pigment inks, but it is dye-based inks, currently used for high resolution printers, which are the most sensitive to light. The dyes – which act as colourants – are composed of very fine particles to ensure that the tiny nozzles used in the production of high resolution images do not become clogged up. The larger particles of pigment inks are more resilient to light energy, but due to their size have a limited application as far as lower resolution printers are concerned. Pigmented inks lack the vibrancy of dye-based inks; their colour gamut is also more restricted.

However, ink manufacturers are consistently producing better quality inkjet inks. Specialist ink manufacturers such as Lyson, supplier of inks for the IRIS printer, have developed improved lightfast dye-based inks; they also manufacture inks for use with many other leading printers. Their Lysonic ink for the IRIS printer has a lightfast rating of 65 to 75 years, when used with Somerset Velvet paper, and has been accepted by many editioners as having good stability. Lyson also produces a monochrome black ink set called Quad Black, which has a lightfastness of over 100 years.

The development of the inkjet printer is continually improving. Print head technology is advancing rapidly with the use of larger print head nozzles to produce high resolution graphics. The large format Epson Pro 9000 released early this year, like the IRIS printer, uses drop-on-demand inkjet technology which is much cheaper to produce and run than continuous inkjet printing. The Pro 9000 has a resolution of 1440 dpi and produces images almost equivalent to the quality of the IRIS printer (which creates images with an apparent resolution of 1800 dpi).

Current research into pigmented ink technology has shown that when the pigment particles are reduced to as little as half their size, the colour gamut and vibrancy of the inks produced with these pigments improves. The colour quality of these inks is almost on a par with dye-based inks with no serious deterioration of light stability. Manufacturers are also introducing the use of six different colour print head cartridges or more to increase ink colour gamuts.

The type of paper is also critical and can dramatically affect the lightfast stability of the inks. Coated papers which hold the ink close to the surface of the media for high colour saturation will reduce lightfastness, but in fact many artists prefer to use uncoated papers. The traditional uncoated papers used by printmakers and watercolour artists generally extend inkjet ink longevity, as the ink is absorbed further into the paper than with coated papers. The ink is given some protection by the paper as it is absorbed, and chemical bonding between the inks occurs when the droplets bleed into one another. These papers have weights above 250 gsm.

The Tektronix printer used by artist Tony Lee is a phase change inkjet printer. The inks used for this printer are composed of dyes suspended in wax and are bought as solid blocks. The printer heats up the wax and then sprays it on to a surface through a fine nozzle as normal ink jet printers. The printer produces highly saturated solid colour images with most of the ink being held on the surface of the paper, but the wax binder does not provide protection for the dyes against light and is subject to surface abrasion. This type of ink jet printer cannot be recommended for the long term but, for artists, its excellent colour quality and saturation outweigh its disadvantages. To overcome the problem of the print's sensitivity, artists are reprinting any of the images sold to buyers, on request – a whole new way of looking at art collecting or another bag of worms, depending on your point of view.

Manufacturers are also trying to overcome the problem of light sensitivity by offering specialist coatings for ink jet prints. Recent research into the use of chelate compound agents on wax based inks, such as the type used with dye sublimation and the Tektronix printers, suggests they do reduce the inks' sensitivity to light.

The lightfastness of most of the inks supplied for ink jet printers may fall short of The Fine Art Trade Guild standard, but there are inks available with lightfast ratings above 60 years at least. The quality of these printers is continually improving and the lightfast standard is bound to be raised. The artist's choice of paper is also an important element. My main recommendation to those using the medium is to use an ultra violet filter when exhibiting the works. Filters will reduce the most damaging wavelengths of light coming into contact with the print. As always, prints should never be placed in strong day or artificial light.

Debbie Glynn is researching the stability of computer-generated prints for a PhD at Camberwell College of Arts

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P.5 REFERENCE

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The preservation and conservation of ink jet and electrophotographic printed materials

Digital printers have become an established tool for the production of fine art and photographic prints. Artists such as Robert Rauchenburg, Chuck Close, Jim Dine and David Hockney have all used and endorsed the medium. There is now an urgent requirement for research into the stability of this new form of artwork. The aims of this project are: i) to establish the archival quality of computer generated produced materials; ii) to identify possible conservation problems associated with this type of material, and to propose treatments to deal with these. Since artists have mostly exploited the use of ink jet and electrophotographic printers, the research has focussed on these areas.

The use of computer printers to produce fine art prints really became established after Graham Nash, the rock musician, realized the potential of large format ink jet printers, in 1989. Being a keen photographer, his interest led him to investigate methods of high quality digital output. He discovered the IRIS 3047, a large format ink jet printer manufactured by Scitex, which was designed for offset proofing[1]. The printer was revolutionary, as it was the first digital printer that was able to produce high-resolution, continuous tone images on a variety of substrates. Nash started to use the machine to print his photographs and then opened up a business called Nash Editions, in California, to offer the services of the printers to other artists[2].

Electrophotographic printers have been exploited by many artists, one of the most famous examples being David Hockney and his 'Home made prints', made in the late 1980's. Hockney experimented with Xerox colour photocopiers and fax machines to produce prints of his designs. He used the colour photocopiers to layer various colours and textures on the paper surface by feeding the paper through the copier machine again and again - up to 12 times - for each colour change[3].

Concern for the stability of digital prints arose after it was found that the inks used with the IRIS ink jet printers had poor light fastness characteristics, and were noticeably fading within only a few months. The archival quality of the inks and papers had originally not been an issue for the manufacturers, because the printers were intended to produce ephemeral graphics and proofs. Research was then undertaken by companies such as IRIS to develop better quality inks, papers and printers. This research has led to the availability of consistently higher standards of media and hardware.

Both ink jet and electrophotographic printers are categorized as non-impact printing (NIP) systems, as they produce images and text on paper without striking the page. NIP is the term given to a number of computer printers including thermal wax transfer, dye sublimation, photochemical systems, etc. The quality of the images produced by ink jet and electrophotographic printers is determined by several different variables, but the most important of these is the printer's resolution.

The resolution refers to the number of either the series of dots per inch for ink jet (dpi) or pixels per inch for photocopiers and laser printers (ppi) produced. Ink jet resolution can range from 300 to 1800 dpi, depending on the printer. A 1800 dpi is achieved through an apparent resolution value, where the individual dot can be varied from 0 to 32 droplets per dot. Electrophotographic systems tend to have a resolution between 300 and 600 ppi depending on the printer. Resolution is variable depending on the configuration of the dots that make up an image, known as the dithering pattern for ink jet printers.

There are three different types of ink jet printers on the market today: continuous ink jet (CIJ); drop on demand (DOD); bubble/thermal ink jet. Two classifications of electrophotographic printers exist: photocopiers; laser printers. Both systems use four colored inks - cyan, magenta, yellow and black (CMYK) – to produce all the colors. The two printing devices are dependent on specialized inks and paper for high quality output. Out of all of the NIP technologies, ink jet systems are the most dependent on the type of ink and paper used with the printer for good quality imaging.

Ink Jet Printers

Ink jet printers require a minute orifice or nozzle from which a tiny stream of uniformly shaped droplets of ink spurts out directly onto a paper surface. Ink must be very fine and fluid so that it may pass through the orifice. For CIJ systems, water-based inks colored with organic soluble dyes are used. The dyes are modified from textile dyes because of their color reliability, solubility in an aqueous medium, and their thermal stability. Other ingredients such as hygroscopic solvents, typically a glycol, are added to the inks to lower the evaporation rate and to allow the ink to penetrate more rapidly into the paper. The DOD and bubble jet printers can utilize a larger orifice. Therefore, the can accommodate solvent-based pigmented inks, but these do not tend to have the same vibrancy or as larger colour gamuts of the dyes.

The liquid ink requires specially coated papers, so that the ink is not absorbed too far into the substrate. These coatings are composed of pigments, latex, fluorescent agents and binders, and are designed to have a very porous structure so that most of the ink is absorbed near to the surface of the paper. However, artists are also using good-quality watercolor and printmaking papers because they like the softening effect that results from the ink flowing along the fibers. These fine art papers can considerably improve the light fastness of an ink jet image, because absorption of the ink by the paper provides some protection against light damage and permits hydrogen bonding between the inks and the cellulose substrate.

Initially, the IRIS printer (which uses CIJ technology) became the preferred system to produce high quality, large format fine art prints. These particular prints have been given the name Glicées, derived for the French word for "spit" or "spurt". However, recently new released printers have been introduced onto the market that can produce images almost equal to the quality of the IRIS but much more efficiently, such as the Epson Pro Series (DOD) printers, which have a resolution of 1440 dpi[4].

The required composition of the inks and paper is not of archival quality (see Fig. 3.47). The presence of dyes in the inks, and the fluorescent agents and latexes in the paper coatings make the prints very unstable and are a cause for concern[5].

Electrophotographic Printers
Electrophotographic printers are based on forming electrostatic images by photoconductive discharge of an electrically charged surface. The charged surface is selectively discharged by exposure to light. The remaining charge is used to attract a colorant, referred to as a toner, which is then fused onto a sheet of paper by heat and/or pressure.

Electrophotographic toners and papers do not have as much limitations as the ink jet media. The toners are made up of a solid mixture of fine resin coated pigments. The paper does require the addition of conductive polymers to prevent the moisture content of the paper becoming too high, as this can prevent proper fusion of the toners to the paper substrate.

Research Project
Research at Camberwell College of Arts has investigated in particular the damaging effects light has on the new media with the conduction of accelerated light fast and natural ageing tests. A colorimeter has been employed to plot the fading rates of different printing types, and comparisons of the results from the two methods of light exposure have been made.

The project is also investigating the effect different spectral distributions have on light fast stability, following the research by conservation scientist David Saunders and Jo Kirby[6].Their research has found that the amount of lux-hours are not necessarily a good method of assessing and stipulating lighting display conditions. It was found that certain wavelengths of light were responsible for photochemical reactions, and the UV part of the spectrum was not necessarily responsible for catalyzing reactions of very sensitive materials. Sensitive colorants such as textile dyes were found to be unaffected by UV light, but wavelengths in the violet, blue and green areas of the visible part of the spectrum were responsible for fading reactions. Therefore, colored filters have been employed with the light-fast tests to research the effect different wave bands of light have on the printing types.

The second stage of the project has focussed on the conservation of this type of printed material. Basic treatments have been reviewed in paper conservation, and their application evaluated. Treatments tested include: mechanical dry cleaning; humidification; washing; de-acidification; solvent application; pressing; paper repair. Testing has been concerned with observations of any detrimental effects that may occur with these treatments.

Standard sample formats, contained on a computer file, have been developed for the experiments. Samples have been obtained from the following ink jet and electrophotographic manufacturers currently being used by artists and photographers: Canon, Encad, Epson, Hewlett Packard, IRIS, Xerox and the ink manufacturer Lyson.

The research will be submitted for a Ph.D. in September 2001, and the results of this project will be published in the following year.

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[1] Scitex America Corporation, 8 Oak Park, Bedford, MA 01730, U.S. www.scitex.com.
[2] Nash Editions has a web site that gives an introduction to how the business was established: www.nasheditions.com.
[3] The stability of David Hockney's "Home made Prints" has been investigated by Heather Norville-Day. Her research found that the photocopy toner under went color change during light fast ageing, except the black toner. A pronounced crazing of the coloring layer occurred, which was more severe

where two or more layers of toner were overlaid on top of one another. Norville-Day, H. "The conservation of faxes and colour photocopies, with special reference to David Hockney's 'Home Made Prints,'" in A. Richmond (ed.), *Modern Works - Modern Problems? Conference Papers* (The Institute of Paper Conservation, 1994), pp. 66-72.
[4] Epson (U.K.) Ltd., Campus 100, Maylands Avenue, Hemel Hempstead, Hertfordshire, HP2 7TJ, U.K. www.epson.co.uk.
[5] Research into the effect ambient environments have on coated papers found that yellowing of the coatings occurred when nitrogen oxide reacted with the antioxidants present in the latexes and fluorescent agents. Ammonia intensified the reaction caused by the nitrogen oxide on the latexes. Mailly, V., J. Le Nest, J. Serra Tosio, and J. Silvy "Yellowing of coated papers under the action of heat, daylight radiation, and nitrogen oxide gas," *Tappi Journal* 80, no. 5 (1977), pp. 176-183.
[6] D. Saunders and J. Kirby, "Wavelength-dependent fading of artists' pigments," IIC Preprints to the Ottawa Congress, Preventive Conservation Practice, Theory and Research (Ottawa, 1994), pp. 190-94.